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CAISSON SICKNESS

AND THE PHYSIOLOGY OF WORK IN COMPRESSED AIR

BY

LEONARD Erskine HILL, M.B., F.R.S.

LONDON
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GENERAL EDITORS' PREFACE

The Editors hope to issue in this series of International Medical Monographs contributions to the domain of the Medical Sciences on subjects of immediate interest, made by first-hand authorities who have been engaged in extending the confines of knowledge. Readers who seek to follow the rapid progress made in some new phase of investigation will find herein accurate information acquired from the consultation of the leading authorities of Europe and America, and illuminated by the researches and considered opinions of the authors.

Amidst the press and rush of modern research, and the multitude of papers published in many tongues, it is necessary to find men of ripe experience, who will winnow the wheat from the chaff, and give us the present knowledge of their own subjects in a duly balanced, concise, and accurate form.

The present volume is the work of one of the Editors, who hopes that the results of his prolonged investigation bearing upon Caisson Sickness will be found of sufficient interest to justify inclusion in the Series.

WILLIAM BULLOCH,
LEONARD HILL.

February, 1912.

PREFACE

In this volume I have gathered together the results of some fifteen years' research into the causation, cure, and prevention of compressed-air illness—a subject of the greatest importance to engineers who build harbours, sink the piles of bridges, and tunnel under the rivers of the great cities of the world by means of compressed-air caissons; also to the navies and mercantile marines, and the pearl and sponge fisheries, which employ divers. The limits of many vast commercial undertakings are set by the toll of life which work in compressed air has hitherto demanded. By the exact methods of scientific investigation and control, work hitherto dangerous can be made safe, and the limits hitherto set to the work extended. In the pearl fisheries off North-West Australia 7 per cent. of the divers lose their lives. They are poor Japanese, ignorant, uncontrolled by scientific method, and periodically tempted to try the rich, untouched banks where shell lies at depths of 20 to 25 fathoms, are frightened back to the shallower, fished-out banks by those dreadful cases of paralysis and death which occur among them.

By a properly selected, trained, and equipped band of divers these beds undoubtedly could be fished with safety, and at a great commercial profit. So, too, the engineer could carry out important works at a pressure which he has not hitherto dared to use.

In compiling this book I have drawn largely on the masterly pioneer work of Paul Bert, "La Pression Barométrique"—a book which has suffered an amazing neglect by English and

American engineers and the medical officers employed by them in compressed-air works.

The two big volumes, "Luftdruck Erkrankungen," by R. Heller, W. Mager, and H. von Schrötter, have been a mine of wealth to quarry in, containing as they do a complete analysis of the literature of my subject up to the year 1900.

Von Schrötter has since brought the subject up to date by further summaries published in the *Hygienisches Zentralblatt*, Bd. III., 1907, and "La Travail dans l'Air Comprimé," Bruxelles, 1910.

The Report of the Admiralty Committee on Deep-Sea Diving (1905) contains the important contributions of John Haldane to this subject, and forms the basis of my discussion of the method of stage decompression which has been introduced into Admiralty practice.

The mathematical calculations on which the Admiralty table of stage decompression is founded have never been published, and so cannot be critically examined. The table is built very largely on theoretical data concerning the circulation of the blood, which cannot be regarded as fixed in the varying states of activity of a man's body.

There is no doubt that the periods of decompression can be greatly shortened by the taking of active exercise during decompression, so as to accelerate the circulation, the ventilation of the lungs, and the escape of the dissolved nitrogen out of the body. The engineer considers the long periods fixed by the Admiralty Committee unpractical. He can safely shorten them if he trains his men to exercise themselves during decompression. I bring evidence to show that the breathing of oxygen at a certain stage in the decompression is of most potent assistance. The London County Council has spent large sums in excessive and, I think, useless ventilation of Thames Tunnel caissons, for carbonic acid has nothing to do with the causation of Caisson Sickness. The money would have been better spent on cooling the working chambers.

Compressed-air work has its humorous side. Two workers in the Tower Bridge caissons were seized with "bends." One danced about with the pain, and he was quickly relieved; the other knelt down and prayed. As the religious exercise proved of no avail, he also quickly betook himself to dancing and found relief.

There is the story, too, of the Town Councillors who went to celebrate the completion of a section of certain tunnel works, and took some champagne into the caisson. On drawing the cork the champagne proved flat, and, thinking it bad, they drank none, all except one, who tasting liked the wine, and drank half the bottle, which he then corked and put in his pocket. During decompression in the air-lock the cork blew out with a loud report, and there was a great commotion, as one Councillor asserted he had been shot. This was nothing to the commotion made by the other who had drunk when the champagne effervesced in his stomach.

I am greatly indebted to all who have worked with me on this subject, in particular Prof. J. J. R. Macleod, Mr. Major Greenwood, and Mr. F. J. Twort. Dr. Paul Fildes, Dr. C. Ham, Mr. R. A. Rowlands, and Mr. H. B. Walker, have also given much help. Mr. E. W. Moir has given me the results of his great experience of Recompression. Mr. E. Tabor has very kindly given me a diagram of the shield employed in the L.C.C. Greenwich Tunnel. Mr. R. H. Davis, of Messrs. Siebe, Gorman and Co., has afforded me the greatest assistance, in giving me valuable apparatus, material, and his experience in the course of the researches, and in lending me blocks of figures of the apparatus used to illustrate this book. The firm of Siebe, Gorman and Co. has shown a most enlightened interest in the value of scientific research. Dr. Martin Flack has been kind enough to read the proofs.

There is much yet to be done, but I hope this book may be of some little use in furthering the safer use of compressed air.

LEONARD HILL.

LOUGHTON,
January 12, 1912.

CONTENTS

ERRATA

Page 32, line 15, *for* “calcium phosphate” *read* “calcium phosphide.”

,, 126, footnote, *for* “W. G. Parkinson” *read* “Dr. J. Parkinson.”

,, 150, table, *for* “Atmospheres absorbed” *read* “Atmospheres absolute.”

,, 157, line 23, *for* “0·3” *read* “0·03.”

,, 210, line 3 from bottom, *for* “inhaling” *read* “exhaling”; bottom line, *for* “per cent.” *read* “per mille.”

,, 236, lines 9, 11, and 13 from bottom, *for* “hours’” *read* “hours.”

CAISSON SICKNESS

AND THE

PHYSIOLOGY OF WORK IN COMPRESSED AIR

CHAPTER I

THE NAKED DIVER

While some explore the confines of the air, others no less venturesome seek the world which lies beneath the waters, and in the curious gear of the diver creep with the crabs through the marvellous scenery of the sea. By means of compressed air man has kept out the waters, and built and tunnelled in dryness under the rivers of the great cities of the world. By the breathing of oxygen he has attained in a balloon to an altitude that tops the Himalayas by a mile; on the other hand, he has never attained to, and probably never will attain to, the bottom of the sea, in the greatest depths of which there is a superincumbent pressure of some five miles of water, or 800 atmospheres.

It is rash to say that anything is impossible, but physical and physiological knowledge alike point to the impossibility of man ever translating his body beyond the atmosphere of the earth, or down to the bottom of the ocean. The only way by which he could reach the abysm of the sea would be by hermetically sealing himself in a metal ball, strong enough to stand the compressive force of 1,000 atmospheres. He would be none the wiser if so enclosed he were lowered as a plummet to the bottom.

It is to the physiologic conditions of the diver and the worker in compressed air that this volume is devoted.

THE NAKED DIVER.

From the earliest time naked divers have carried on the profession of sponge and pearl fishers, notably in the Mediterranean Sponge Fisheries and the Ceylon Pearl Fisheries. Spanish writers of the sixteenth century speak of the extensive employment of divers in the Gulf of Mexico, and mention the bleeding from mouth and nose and ears from which the divers suffered.

It was not until 1837 that Siebe perfected his closed diving dress, and several years elapsed before it was introduced into the pearl and sponge fisheries.


FIG. 1.—JAPANESE WOMEN DIVERS (UTAMARO).

Denayrouze brought the diving dress into use in the Grecian Archipelago some forty years ago, and even now so large is the population dependent on those engaged in the fisheries that regulations have been made both in Ceylon and Turkey restricting the use of diving dresses within the three-mile limit.

The naked diver is trained from childhood to his trade. Mothers are said to hold their children under water to practise their powers of endurance. In the island of Ashima (Province of Idsu), in Japan, it was customary for the women to dive for the shell Awabi. The women ruled the men, who stayed at home and minded the baby. A distinguished Japanese artist tells me that as a child he heard the origin of this custom lay in the fact that the very cold water in the depths had a perishing effect on the testicles of the men. It was reputed that the sea-bream attacked the men and bit off their testicles, but it was really the cold. The women, having no vital parts so exposed to cold, took over the work, both for the men's sake and their own.

The naked divers go to astounding depths: 60 to 70 feet is quite a usual depth, but rarely, it is said, 120 to 130 feet is attained. The depth it is possible to go to is limited by the time it takes to get to the bottom and back. The divers shorten the time of descent by grasping a heavy flat stone, or by putting the feet in a stirrup attached to such a stone—in this case plunging down feet foremost. A rope is attached to the stone, and the diver either may be hauled up by the rope or ascend by his own efforts. Some of the deep-water divers put a horn clip on their nose, an oiled wad in their ears, and a small bit of oiled sponge in the mouth.

The time that the divers are said to stay under water is often greatly exaggerated. Robert Boyle writes thus: "Those that dive for pearls in the West Indies are said to be able to stay a whole hour under water; and Cardan tells us of one Calamus, a diver in Sicily, who was able to continue (if Cardan neither mistake nor impose upon us) three or four times as long. Not to mention, your Lordship, that you have yourself oftentimes seen in England a corpulent man who is wont to descend to the bottom of the Thames, and bring out of deep holes, at the bottom of the banks, large fishes alive in his hands." Cardan, the mathematician, unable to solve an equation, is reputed to have hired a band of cut-throats to waylay, carry to a cave, and steal the solution from a rival mathematician. He therefore would not stop at a mere imposition. As to the truth of this and the use of oiled sponges, Boyle says: "An ingenious man of my acquaintance, who is very famous for the useful skill of drawing goods, and even ordnance, out of sunk ships, being asked by me how long he was able to continue at the depth of 50 to 60 feet under water, without the use of respiration, confessed to me that he cannot continue above two minutes of an hour without resorting to the air, which he carries down with him in a certain engine (whereof I can show your Lordship a description). Another thing I also learned of him by inquiry, that was not despicable: for, asking him whether he found any use of chewing little sponges, dipped in oil, in his mouth, when he was perfectly under water, and at a distance from his engine, he told me that by the help of these sponges he could much longer support the want of his wonted respiration than he was able to do without them. The true cause of which would, perhaps, if discovered, teach us something pertinent to the problem touching the respiration of fishes."

In regard to the respiration of fishes, it is difficult to see what Boyle had in mind; but as to the use of the oiled sponges

Edmund Halley also had something to say at a meeting of the Royal Society in 1717, he then being secretary, and Sir Isaac Newton president :*

"Considering how small a Quantity of Air can be supposed to be contained in the Pores or Interstices of a Sponge, and how much that little will be contracted by the Pressure of the incumbent water, it cannot be believed that a supply by this means can long subsist a Diver. Since by Experiment it is found that a gallon of Air, included in a Bladder and a Pipe reciprocally inspired and expired by the Lungs of a man, will become unfit for any further Respiration in little more than one Minute of time ; and though its Elasticity be but little altered, yet, in passing the Lungs, it loses its vivifying Spirit, and is rendered effete. . . . I shall not go apart to show what it is the Air loses by being taken into the Lungs, or what it communicates to the Blood by the extreme ramifications of the Asperia Arteria." He recognizes that there is no proof of any communication between these—the bronchial tubes, and veins and arteries.

The chewing of the sponge and swallowing of the oil probably has an inhibitory effect on the respiratory centre. In a series of experiments on the power to hold the breath, made by Martin Flack and the writer, we have noted that swallowing movements are generally made when the subject nears the breaking-point, and wishes to extend the period of breath-holding to the utmost. Although oil can hold in solution more than five times as much oxygen and nitrogen as water (Vernon), the oiled sponges at the most could only add a centimetre or two of oxygen to the available supply, and the effect gained by chewing the sponge cannot be attributed to this.

When the naked diver returns to the surface, he may either rest three or four minutes and then dive again, or return to the boat and let another take his place ; and the work thus proceeds during the heat of the day. The warmth of the tropical sea renders this form of diving possible. Martin Flack and I have found it more difficult to hold the breath with the face immersed in iced than in warm water, for the discomfort of the cold adds itself to the impulsion to breathe. The average for sixteen experiments was forty-two and a half seconds for warm, and twenty-nine and a half seconds for cold, water.

The most remarkable account of the exploits of naked divers

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* Transactions of the Royal Society, xxix., 1717.

in very cold water is cited by Heller, Mager, and von Schrötter,* from a book of travels in the Northern Sahara, by Colemieu :

"The water-supply is obtained from artesian wells which are up to 130 feet in depth. The 'eye' of these wells often gets stopped up with sand, brought up from below by the spring, or blown in from above. The difficult and dangerous work of cleaning the 'eye' is carried out by a guild of divers. A single diver brings up as much sand as he can in three to four minutes ! Not infrequently a diver loses his life over this work. The descent and ascent are made by means of ropes which are let down the well. The diver stops up his ears with wax, and, getting into the water, waits a while to get used to the temperature. He then gives the signal, fills his lungs as much as he can with a couple of breaths, and sinks under. His comrades can follow his movements by the two ropes which reach to the bottom. Three minutes and two seconds have already gone by, and one is beginning to get anxious, when he rises to the surface half asphyxiated and almost unconscious. His comrades grip him and hold him while he gets his breath, and then he climbs out and goes and warms himself by the fire, while the next takes his turn. The young men of the guild seem strong and healthy, the old lean and straight-chested, but they stay under longer and suffer less. The young men are too hasty, and that tells against them. The pulse is noted as being diminished in frequency—*e.g.*, 86 before the descent, and 55 immediately after the ascent," a diminution no doubt due to the inhibitory action of the vagus nerve, the centre of this nerve being excited by the want of oxygen in the first stage of asphyxia.

As to the hæmorrhages so frequently noted as occurring in naked divers, we must bear in mind that the arterial pressure is raised during the asphyxial period both by the powerful beats of the heart and by vaso-constriction, while the venous pressure is raised by the fixation of the thorax and cessation of the respiratory movements, which further the return of blood to the heart ; also by the compressive action of the powerful muscular movements of the diver. The air in the mouth, nose, ears, and lungs is compressed during the descent, and as the pressure equals that of 4 atmospheres at a depth of 100 feet, the air therein should be reduced in this case to one-fourth of its volume. Owing to the rigidity of the wall of the nose and ear cavities, the

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* *Luftdruck Erkrankungen*, Wien, 1900.

full reduction in volume, and corresponding equalization of pressure within and without, may not take place there. If this is so, the pressure of the air will be less than the pressure of the water on the rest of the body, and a cupping effect must take place. The ear is connected with the throat by a passage—the Eustachian tube—and if this and the way into the nasal cavities are freely open, the pressure will be equalized, and no cupping effect occur. The volume of the air in the lungs will not be sensibly reduced by the O_2 used, for the CO_2 output will be of about the same volume; but during the stay at the bottom some of the nitrogen and oxygen of the air enclosed in the cavities must pass into solution in the blood and be carried to the tissue fluids. On rapidly returning to the surface, there takes place an expansion of the air which has been thus diminished in volume. No cupping effect, however, can be produced thereby so long as the diver keeps open the communications between the nose, middle ear, and lungs, for the mobility of the diaphragm will insure a reduction or increase of volume of the air in the thorax in proportion to the pressure of the surrounding water. The air in his lungs must be compressed to one-half its volume at 33 feet, to one-third at 66 feet, to one-quarter at 99 feet. Therefore he must fill his lungs well before diving, to prevent the over-displacement of his heart by the ascent of the diaphragm. The practised diver no doubt fills his lungs well, keeps open his Eustachian tube by swallowing, and so times his stay at the bottom that the asphyxial congestion of the bloodvessels is not brought to the rupture-point during the efforts of the ascent. In the case of the whale, which sounds to depths of 200 fathoms or more, it is an unsolved problem what happens to the air in its lungs. Do the parts allow the full compressive action to take place? Is the air dissolved in the blood in proportion to the partial pressure? If so, what happens when the whale returns to the surface? The anatomical arrangements must either allow compression of the lungs to the smallest size, or else water must enter the lungs and bring about the compression of the air. It is impossible that any rigid structure should hold off the pressure, for if this were the case, a cupping effect and hæmorrhage into the lungs would take place.

Some naked divers put wool soaked in oil in their ears. This hinders the entry of water when the air in the auditory meatus is compressed.

The divers carry out vigorous movements under water, and thus the time of submergence is very limited. The bearable percentage of carbon dioxide in the lungs is rapidly reached, and about one minute seems to be the usual limit. By a few seconds' deep breathing just before the dive they seek to prolong the time as far as possible. It is said that by practice they extend the time, and that the best divers may attain to two minutes at the end of the sponge-fishing season.

The period which the naked diver can stay under water depends on his power to withstand the excitatory effect of the carbon dioxide and other acid in the blood, the increasing concentration of which impels the respiratory centre into such a state of exaltation that finally a point is reached at which it can no longer be inhibited by voluntary effort. It must require much practice and a nice judgment on the part of the diver to leave the right margin of time for those efforts which are necessary to attain the surface from any considerable depth.

The work of Haldane and other English physiologists has demonstrated that the inspiratory centre is excited more or less by the relative concentration of acid (the hydrogen ion) in the blood. In conditions where there is want of oxygen, the oxidative processes in the tissues do not proceed wholly to the end-products —water and carbon dioxide—and half-way products accumulate, such as lactic acid. The lactic and carbonic acids summate their effect on the respiratory centre. The naked diver suffers not only from the rising concentration of carbon dioxide in the blood, but from the falling concentration of oxygen, for this leads to the increased formation of lactic acid in the muscles and its appearance in the blood. It may be detected both in the blood and urine (Ryffel).*

By deep breathing before the dive carbonic acid may be washed out of the body, and its concentration notably reduced. At the same time the concentration of oxygen is raised in the lungs, the hæmoglobin of the venous blood becomes more saturated with oxygen, and any traces of lactic acid which may be present in the muscles are oxidized. The naked divers are generally in the habit of taking deep breaths before each dive.

By massage and short preliminary runs, such as the athlete takes before a race, the circulation in the muscles is brought into the active state, the carbonic acid washed out, and any lactic

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* *Journ. Physiol. Proc.*, xxix. 39, 1909.

acid oxidized. The movements of the muscles aid greatly in the circulation of the blood, as by their contraction and relaxation they pump the blood onward, the valves in the veins preventing the back return. Violent muscular movements may for the time being altogether impede the circulation, for no blood can pass through the contracting muscles, which then work with a deficient oxygen supply. Thus lactic acid is formed. This is always the case in rapid running or climbing movements.

Martin Flack and the writer have shown that by deep breathing oxygen for two or three minutes, and then holding the breath with the lungs full of oxygen, the breath can be held easily for astonishingly long periods of time, five to six minutes being attained by most subjects, and as long as nine minutes two seconds by one subject.

Similar results were obtained by Vernon,* thus :

EFFECT OF FORCED BREATHING.

Duration of Forced Respiration.	Duration of Subsequent Apnœa (Period of Holding Breath).		Composition of Alveolar Air (Air in Lungs) at End of Apnœa.	
	Min.	Sec.	CO_2 per Cent.	O_2 per Cent.
0	0	42	6·6	11·1
0	0	42	6·9	9·1
1	2	21	6·1	8·2
3	3	21	—	—
5	3	2	5·5	5·8
5	3	53	—	—
6	4	5	5·9	3·7

The respiration was increased to about 30 to 35 per minute, and made as deep as possible. After the final deep respiration, the nostrils were closed by a clip.

The results show that by forced breathing alone the period of holding the breath was raised from forty-two seconds to four minutes five seconds. The CO_2 is removed from the blood and tissues by the increased ventilation of the lungs, and our figures show that when the partial pressure of CO_2 is lower, a lower partial pressure of oxygen can be borne—*e.g.*, the breaking-point occurred with 6·6 to 6·9 per cent. CO_2, and 11·1 to 9·1 per cent. O_2; with 5·5 to 5·9 per cent. CO_2, and 5·8 to 3·7 per cent. O_2.† If, as seems to be the case, the breaking-point depends on the

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* *Journ. Physiol. Proc.*, xviii., p. 38, 1909.

† *Journ. of Physiol.*, p. 77, 38, 1908.

concentration of acid (H ions) in the blood and respiratory centre, it follows that the lower the concentration of CO_2 the more lactic acid can be endured arising from want of O_2.

FORCED BREATHING PLUS OXYGEN (VERNON).

Approximate Percentage of Oxygen in Gas last Breathed.	Duration of Forced Respiration.	Duration of Subsequent Apnœa.		Composition of Alveolar Air at End of Apnœa.	
		Min.	Sec.	Co_2 per Cent.	O_2 per Cent.
74	0	1	7	7·2	15·7
74	0	1	19	7·7	14·2
70	1	3	38	7·4	40·2
95	1	4	18	8·8	32·6
74	3	6	34	7·9	56·0
85	5	6	2	8·0	56·3
74	6	8	13	8·5	46·2
74	8	7	27	7·8	11·3*

The figures show that a higher concentration of CO_2—on the average, 1·7 per cent. higher—can be stood when there is plenty of oxygen in the lungs and the production of other acid products of metabolism is at a minimum. The world's record for a professional diver remaining under water in a tank is 4 minutes 45½ seconds. By combining oxygen inhalation with forced breathing it should be possible for naked divers to remain under water as a rule not one, but two to three minutes, taking into account that the time will be shortened by muscular effort. The great utility of this is obvious-

Martin Flack and the author found that under ordinary conditions the " breaking-point " is reached when the partial pressure of CO_2 in the alveolar air of the lungs has risen to 6 to 7 per cent. of an atmosphere and the oxygen fallen to 9 to 10 per cent. of an atmosphere. On breathing the expired air in and out of a small bag, we found that the CO_2 rose to about 8 per cent. and the oxygen fell to about 8·5 to 4·5 per cent. of an atmosphere. before the breaking-point occurred. We explain the improvement produced by the use of the bag thus—the holding of the breath produces a mechanical obstruction to the circulation, owing to the cessation of the respiratory pump ; while breathing in and out of the bag the respiratory pump works, and the respiratory centre in the brain obtains a better supply of blood.

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* The lungs were not well filled in this experiment before holding the breath.

The fact that the concentration of CO_2 can be raised by breathing oxygen from 6·7 per cent. to 8 to 10 per cent. of an atmosphere before the breaking-point occurs led us to try the effect of inhalations of oxygen on the power to carry on muscular work. Our experiments show that oxygen inhalation enables one to carry out a short severe muscular effort more easily, and with less distress at the time and less after-fatigue.*

Forced breathing, if continued for some minutes, becomes very uncomfortable, and to continue it is not an advantage, but a disadvantage, in regard to the holding of the breath afterwards. During forced breathing the circulation is impeded. The pulse becomes weak and almost disappears synchronously with each inspiration. Readings of systolic blood-pressure showed a considerable fall synchronously with each inspiration. On radiographing the heart, we observed that the heart-shadow becomes smaller during the forced inspiration, and swells out on expiration. The return of blood from the abdominal veins to the heart is impeded by the forced inspirations. The forced breathing produces curious feelings of tightness round the head, neck, or chest, numbness of the limbs, and tingling sensations. The hands become blue and cold, and are drawn into a semiflexed spastic posture, and exhibit tremor. The breathing becomes periodic, waxing and waning, the speech blurred, the mental state dazed, the subject ceases to exactly follow by sight or hearing what is going on around him. If oxygen is breathed forcibly instead of air, the symptoms are not so marked, and the breathing can be continued longer and with greater force and comfort.

The symptoms described above are chiefly due to the washing out of CO_2 from the body and the reduction of the normal concentration of acid in the blood. That this is so is shown by the fact that breathing in and out of a small bag, which concentrates the expired CO_2 almost immediately, relieves the symptoms, and enables the forced breathing to be carried on with greater power. The fact remains that the breathing of oxygen allows one to go on forcibly breathing until the CO_2 in the lungs is washed out down to the lowest possible level, even to 1·5 per cent. in place of the normal 5 per cent. of an atmosphere, and delays the onset of the symptoms. There are thus two factors at work—the abnormal partial pressure of CO_2, and the want of

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* *Journ. Physiol.*, 347, 40, 1910 ; *Brit. Med. Journ.*, August 22, 1908.

oxygen produced by the impediment to the cerebral circulation produced by the forced breathing.*

The result of the whole research is to show that the most favourable effect can be obtained by moderately deep abdominal breathing. In spite of less ventilation the breath can be held longer, because the blood is circulated better during the period of deep breathing. *The diver should breathe deeply for two minutes, and fill his lungs from a bag of oxygen just before diving.*

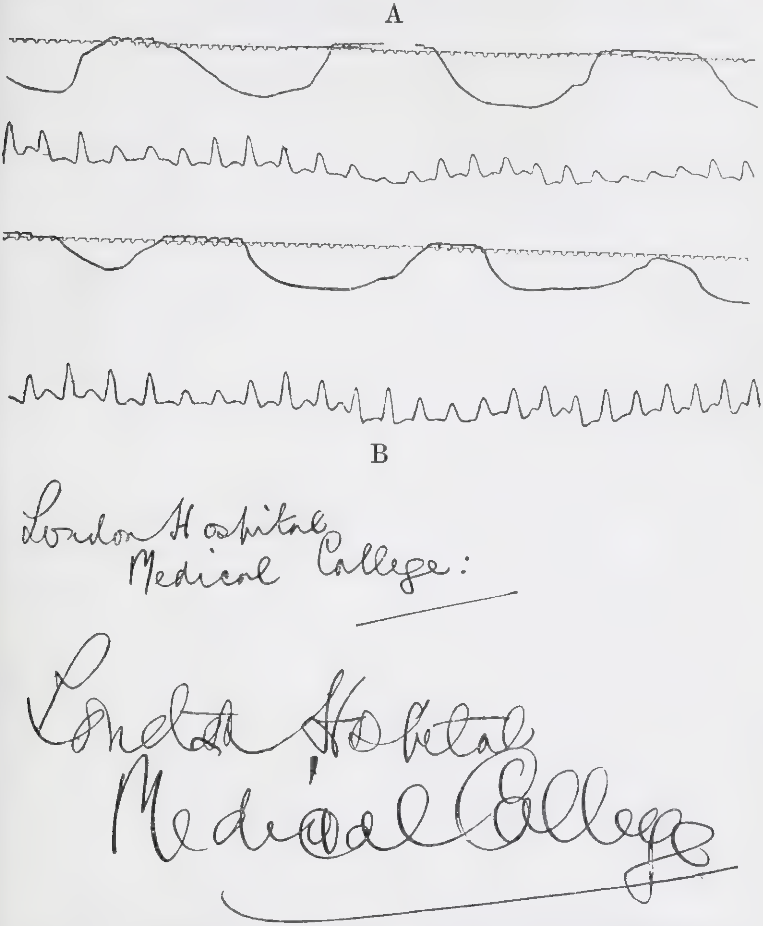

Fig. 2.—A, Pulse during Deep Breathing of Air; B, of Oxygen. The upper curve marks respiration in each case. Inspiration is upwards. The disordered writing after forced breathing of air is shown below.

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* The dissociation of oxyhæmoglobin depends on the pressure of CO_2 in the tissues.

DEEP BREATHING AIR. DEEP BREATHING OXYGEN.

TABLE SHOWING AMOUNT OF WORK DONE UPON WORK MACHINE (RAISING SIXTY POUNDS THROUGH NINETEEN INCHES), WITH BREATH HELD.

Five Minutes' Interval between the Successive Experiments.

Subject.	1. After Normal Inspiration.				2. After Deep Breathing Air.				3. After Deep Breathing Oxygen.				Duration of Deep Breathing in Minutes.	Remarks.
	Number of Pulls.	Time in Seconds.	Amount of Work done in Foot-Pounds.	Work per Second in Foot-Pounds.	Number of Pulls.	Time in Seconds.	Amount of Work done in Foot-Pounds.	Work per Second in Foot-Pounds.	Number of Pulls.	Time in Seconds.	Amount of Work done in Foot-Pounds.	Work per Second in Foot-Pounds.		
L. H. ..	13	18	1,235	68·610	33	43	3,135	72·900	59	73	5,605	76·780	3	In (1) on another occasion, 12 in 19″.
M. F. ..	23	30	2,185	72·830	60	70	5,700	81·429	69	78	6,555	84·038	2½	
R. A. R.	11	17	1,045	61·470	34	45	3,230	71·770	49	60	4,655	77·586	3	In (3) held breath 10 secs. before starting work.
J. M. ..	17	23	1,615	70·217	30	50	2,850	57·000	70	85	6,650	78·235	3	Very marked group-breathing during deep breathing air.
L. H. ..	15	16	1,425	89·060	39	45	3,705	82·530	65	68	6,175	90·808	2	Working as hard as he could.

SIMILAR TABLE, GIVING ANALYSES OF ALVEOLAR AIR AT THE END OF THE EXPERIMENT.

Subject.	Number of Pulls.	Time in Seconds.	Amount of Work done in Foot-Pounds.	Work per Second in Foot-Pounds.	Number of Pulls.	Time in Seconds.	Amount of Work done in Foot-Pounds.	Work per Second in Foot-Pounds.	Number of Pulls.	Time in Seconds.	Amount of Work done in Foot-Pounds.	Work per Second in Foot-Pounds.	Duration of Deep Breathing in Minutes.	Remarks.
L. H. ..	19	23	1,805	78·478	35	37	3,325	89·860	57	59	5,415	91·780	2	
	(% CO_2, 7·68 ; % O_2, 8·31)				(% CO_2, 7·37 ; % O_2, 7·09)				(% CO_2, 9·38 ; % O_2, about 50)					
R. A. R.	24	26	2,280	87·690	44	48	4,180	87·080	63	66	5,985	90·682	2	Before (2) ventilated 133 litres, (3) 134 litres.
	(% CO_2, 7·807 ; % O_2, 9·02)				(% CO_2, 6·408 ; % O_2, 5·203)				(% CO_2, 8·885 ; % O_2, over 50)					

Subject.	1. After Full Inspiration.		2. After Deep Breathing Air, 2 Mins.			3. After Deep Breathing Oxygen, 2 Mins.			Remarks.
	No. of Yards run.	Time in Seconds.	No. of Yards run.	Time in Seconds.	Ventilation in Litres during Deep Breathing.	No. of Yards run.	Time in Seconds.	Ventilation in Litres during Deep Breathing.	
L. H. . .	98	$21\frac{3}{5}$	125	31	104·0	215	52	116·0	Went very blanched in (2).
C. W. . .	125	$23\frac{3}{5}$	159	$32\frac{2}{5}$	75·0	183	$38\frac{1}{5}$	65·5	Much easier on O_2.
J. M. . .	99	$21\frac{4}{5}$	155	28	111·0	192	$38\frac{3}{5}$	112·5	
D. M. . .	133	$26\frac{3}{5}$	180	$36\frac{2}{5}$	99·0	210	$39\frac{4}{5}$	71·5	Association footballer in training.
S. E. . .	98	$21\frac{2}{5}$	—	—	—	420	110	92·5	In (1) went purple, then very blanched. In (3) see text.
M. F. . .	101	$23\frac{2}{5}$	145	$34\frac{2}{5}$	136·0	235	56	143·0	
A. W. . .	94	$24\frac{2}{5}$	180	55	98·5	210	59	93·0	In (3) ran much faster at start.
R. A. R.	113	$29\frac{3}{5}$	150	$35\frac{2}{5}$	122·0	256	$62\frac{3}{5}$	124·0	
R. F. F.	120	$26\frac{1}{5}$	150	$32\frac{2}{5}$	70·0	240	53	87·0	
W. M. C.	114	33	109	27	Moderate	245	65	Moderate	
					Alveolar Air CO_2 O_2			Alveolar Air CO_2 O_2	
L. H. . .	85	23	113	32	6·990 4·03	189	48	10·715 over 50	After (1) felt very bad. After (3) sweating—comfortable.
M. F. . .	100	28	129	$38\frac{1}{2}$	6·200 4·09	199	59	9·190 over 60	In (2) felt heart very much. In (3) no heart symptoms.

The blood-pressure of A. W. fell to 90 during deep inspirations, and rose to 120 during the expirations. After the deep-air run it was 140, and the frequency of the pulse 148; after the O_2 run, 155 and 148. The pulse was irregular after the air, and not after O_2 runs.

The author has constructed an oxygen generator and inhaler suitable for the use of naked divers. A supply of oxylithe can easily be carried, and the oxygen generated as required (Fig. 4).

The previous tables show the power of untrained men to do work with the breath held after—(1) quiet breathing, (2) deep breathing air, (3) deep breathing oxygen. The work performed was the lifting of a 60-pound weight through 18 inches on a "pile-driver" arrangement, the rope being attached to both a handle-bar and a foot pedal, so that the two arms and a foot could be brought into play.

Oxygen notably increased the amount done and the duration of the effort. J. M., for example, pulled 17 in 23 seconds after ordinary breathing, 30 in 50 seconds after deeply breathing, and 70 in 85 seconds after deeply breathing oxygen. The analyses of the lung air at the end of this work, and at the end of periods of running with the breath held, taken at the breaking-point, showed that a very high partial pressure of CO_2 (up to 11 per cent. of an atmosphere) was borne after the oxygen breathing. R. A. R. ran 113 yards in $79\frac{3}{5}$ seconds after ordinary breathing, 150 yards in $35\frac{2}{3}$ seconds after deeply breathing, and 256 yards in $62\frac{3}{5}$ seconds after deeply breathing oxygen. In every case, both of pulling and running, the subjects pronounced on the greater ease with which the work was done and absence of cardiac distress.

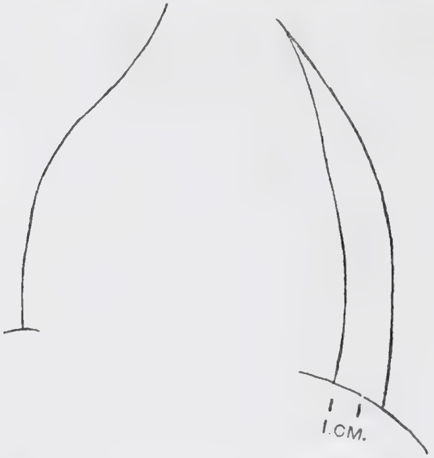

Fig. 3.—Radiographic Outlines of Heart.

The heart shadow is smaller during forced inspiration.

Ryffel found an increase of about 800 milligrammes of lactic acid in the urine passed after he had run two-thirds of a mile, with much dyspnœa. The breathing of oxygen during such an effort diminishes the amount of lactic acid formed, but does not prevent its formation, because the circulation in the muscles is partly strangulated by the frequency and violence of their contractions. T. Feldman, working with the author, has found 244 milligrammes of lactic acid in the urine passed after running up and down a flight of stairs ten times; and 137 milligrammes after performing the same effort while breathing oxygen. By properly grading the work, no lactic acid was produced while oxygen was breathed. Feldman performed the same amount of work under the same conditions, carrying the Siebe-Gorman-

FIG. 4.—OXYGEN GENERATOR AND INHALER.

The generator held in the right hand consists of a metal box with screw lid. Into this two blocks of oxylithe are placed. The breathing bag is squeezed empty of air, and a pint of water is introduced into it through the mouthpiece; the mouthpiece is clipped, and the bag elevated, so that the water enters the generator. Oxygen is liberated, and a caustic soda solution formed—$Na_2O_3 + H_2O = 2NaOH + O_2$. The subject puts a clip on his nose and inhales in and out of the bag, shaking the solution round meanwhile to absorb the exhaled CO_2.

Fleuss rescue apparatus for use in mines. In one case he breathed air, and in the other case oxygen supplied by this apparatus. These experiments show how an adequate supply of oxygen delays the rise in the concentration of acid in the blood.

In the case of S. E., the laboratory attendant, who ran holding his breath after oxygen 470 yards in 110 seconds, we noticed that he "wobbled" in his course, and knocked his feet together in the last lap. We stopped him, or he would have gone on and fallen. Thinking he was faint, we bent him double and told him to breathe. He took no notice. On removing the clip from his nose, he took a stertorous breath. We laid him on the floor, and after about half a minute he got up on to a chair and looked round him in a dazed condition, and recovered his senses in about a minute. He had been unconscious of all that had happened during this time. His colour was good, and there was no cyanosis. When on the floor his pulse was found to be good. From the colour of his face and the results of other analyses of alveolar air, there can be no doubt he still had plenty of oxygen in his lungs, and we conclude that his alveolar CO_2 tension had risen to such a point that he had become comatose, and was running automatically. There was no danger to life, owing to the ample supply of oxygen. It is possible that divers, after breathing oxygen, might similarly become comatose. It would be a necessary precaution, therefore, that they should have a rope attached to them, so that their comrades may haul them up if their usual time of submersion is exceeded.

CHAPTER II

THE EVOLUTION OF THE DIVING DRESS AND BELL

The ingenuity of primitive man must have led him, soon after he fashioned large clay pots, to see that by fastening one over his head, he could descend under water, and breathe the air confined and compressed in the pot. Such bell-like vessels are chronicled by Aristotle and Arianus as being part of the warlike equipment of Alexander the Great, and as being employed for the loosening of anchors and cables. Aristotle says that the elephant is given a trunk by which it may breathe while in the water, just as a diver has an instrument provided for him by which he can draw in air when under water. A breed of aquatic elephants has just been rediscovered in Central Africa, which so uses the trunk; the existence of these was probably known in ancient times. Pliny mentions divers employed in warfare who breathed through a tube, the upper end of which floated on the surface of the water. He also writes of a man who had some fishlike apparatus by means of which he passed unseen through the enemy's fleet.*

In the time of the Emperor Constantine it is recorded by Xiphilinus that divers, fitted with bells covering their heads, carried Grecian "fire" into the enemy's fleet. Julius Cæsar describes a diving apparatus made of leather, and varnished to keep out the water. Coming to the Middle Ages, Roger Bacon is credited with having made a diving bell.

In Vegetius's "De la Militari" (1511) there is engraved the figure of a diver dressed in what appears to be a leathern suit, with a helmet enclosing the head, to which a breathing tube is attached, leading to a float on the surface. Vegetius's device was used by pirates in the Black Sea for concealing themselves from the enemy as late as 1784. At the time of the discovery

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* Brize-Fradin, "La Chémie Pneumatique Appliquée aux Travaux sans l'Eau," Paris, 1808. Cit. after Bert.

of America the craft of diving excited much interest, and was written about under the curious title of "Ars Urinatoria"—a title which probably owed its origin to the employment of bladders for breathing from. The great artist-scientist, Leonardo da Vinci, interested himself both in problems of flight and diving.

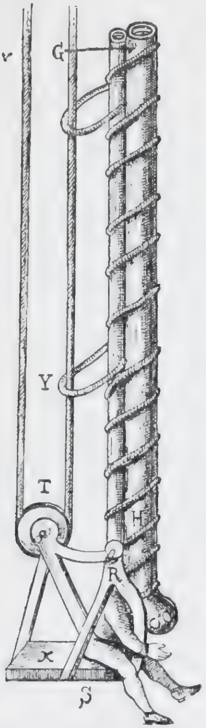

Fig. 5.—The Diving Apparatus of Lorini.

In 1538 two Greek divers gave an exhibition before Charles V. and thousands of spectators, being lowered into the Tagus sitting in a diving bell with a lighted torch, which was still burning, they being unwetted on their return. Lorini, in 1609, busied himself over the production both of a square diving bell, and the curious device shown in Fig 5. The pipe, at the bottom of which the man's head is enclosed, was made of leather stiffened with iron hoops and rods placed lengthwise. The use of all such pipelike devices is only possible in a few feet of water, because, on breathing the air through such a pipe, the lungs are exposed to atmospheric pressure, while the body is exposed to atmospheric pressure plus the pressure of the superincumbent water. This produces a dangerous cupping effect on the lungs, and must result, not only in great difficulty of breathing, but in the produc- of hæmorrhages into the air-way.

Kessler ("De Secretis," 1616) describes a barrel-like apparatus — "an aquatic doublet" — made of leather and hoops, fitted with a window and weights for sinking it under water. Wilkins, in the *Mathematic Magazine*, 1648, mentions a diving-boat constructed by Cornelius van Debrell, a Dutch physician. P. Mersenius also speaks of a submarine boat in his "Tractatus de Magnetis Proprietatibus," 1638. Robert Boyle* states that this boat was to be used and rowed under water, and was actually tried in the River Thames by order of James I. It carried twelve rowers and passengers. "Debrell conceived that it is not the whole body of the air, but a certain spirituous part of it, that fits

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* "Experiments Physico-Mechanical," 1647.

for respiration, so that, besides the mechanical contrivances of his boat, he had a chemical liquor, the fumes of which, when the vessel containing it was unstopped, would speedily restore to the air, fouled by the respiration, such a portion of vital parts as would make it again fit for that office." This liquor was discovered by Debrell's son-in-law, a physician, and the secret of its preparation was disclosed to one other only, who told it to Boyle. The liquor probably was some alkali which absorbed carbonic acid. We have here the germ of a method now in use in submarines, wherein peroxides of the alkalies are used to restore the vital properties of the air.

Lord Bacon describes a diving apparatus * which consisted of a metal bell, which was lowered down full of air into the water, and rested on a tripod, so that the diver, when wanting air, could put his head into it and breathe, and then continue his work. This kind of apparatus, no doubt, was the one widely employed both in classical and medieval times.

George Sinclair slung by four chains a foot-rest of lead, weighing 130 pounds, below a leaden bell, which was about 3 feet high and 3 feet wide. Standing on the foot-rest, with his body in the bell, he was lowered down to the wreck of a ship of the Spanish Armada off Mull, lost in 1580, and recovered treasure from it in 1665. In the last few years salvage operations have been renewed on this very wreck from which Sinclair had the first pickings. Two years later an American, William Philipps, salved by the same means a large sum of gold at a depth of 46 feet from an English ship sunk off San Domingo.

John Christ Sturmius, a professor at Altdorf, 1685, constructed a bell of wood 13 to 14 feet high, with iron hoops, under the lower edge of which leaden weights, 60 to 80 pounds, were hung. The diver sat on a bench in the middle of the bell, and signalled to the surface by means of a rope. He suggested the taking down of bottles of air to restore the air in the bell.† It was observed and recorded at this time that while one man could endure two hours' breathing in the bell, another could only outstay an hour, and the conclusion was drawn rightly that some other factor than the compression of the air came into play *in aere non difflato*. Modern science explains this individual peculiarity by the varying

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* "Organi novi Libri," lib. ii., cap. 50, 1645.

† "Collegii Experimentalis sine Currosi pars Secunda," Nürnberg, 1685–1701.

CO_2 production and O_2 use in lean or fat, quick or slow working men, as well as the varying power to resist the rising partial pressure of CO_2, and falling partial pressure of O_2 in the bell.

One diver took down a hunter's horn into the bell, and, blowing it, nearly knocked himself off his perch, being seized with vertigo from the violence of the sound.

Borelli,* in 1682, gave to the world the first theoretical conception of a closed diving dress. His invention, as it stood, was quite impractical, but most suggestive of further improvement. The equipment consisted of a metal helmet made to fit close to the neck and chest, and a dress of buckskin. Borelli gives no details, and does not lay insistence on the union of dress and helmet in a watertight fashion. A window of glass is fitted into the helmet, and a tube JKL leads out of the helmet and back into it. At K the tube widens into a leathern bag. Borelli states that by inhaling and exhaling through this tube the air will be freed from moisture, which will condense and be rendered fresh and pure, owing to the action of the surrounding water and its long travel in the tube. For further refreshing the air in the helmet, tubes O and N are supplied, which are provided with taps. The diver, on returning to the surface, is directed to expire through tube O, and draw in fresh air through tube N. The cylinder, girded to the loins, is provided with a piston, which serves for the purpose of compressing the air and so regulating the specific gravity of the diver that he can ascend or descend at will.

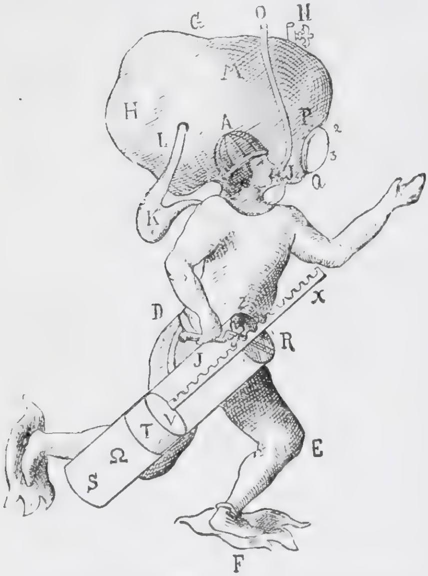

FIG. 6.—THE DIVING APPARATUS OF BORELLI.

The modern diver regulates his specific gravity by adjusting

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* "De Motu Animalium," Rome.

the amount of air in his dress, and Borelli gives us here the germ of this method. Bernouilli justly ridiculed the invention, pointing out that the pressure of the air in the helmet must be kept equal to the water outside to prevent hæmorrhage from the mouth, nose, and ears; therefore the helmet must either be made of leather, compressible, or the man must be wholly surrounded with air, as in the diving bell. Borelli, with far more excuse, fell into the same physical error as certain physicians of the nineteenth century, in thinking that the circulation must be disturbed by the greater resistance to expiration which a man must endure in compressed air, and that the finer bronchial tubes would be strained and, perhaps, ruptured in it.


FIG. 7.—ROBERT BOYLE.

In the case of a man in a diving bell the air-pressure is equally transmitted to all parts of his body, and has no effect.

We now come to the year 1670, when Boyle published his celebrated researches, made with the air-pump contrived by him,* which, viewed in the light of modern science, throws so much light on the true cause of compressed-air illness. He found that aquatic birds could stand evacuation of the chamber in which they were placed little better than other birds. So, too, a sparrow, with its head held under water, was drowned in half a minute, while a duck began to struggle violently in two minutes, in four minutes still gaped, and in six minutes showed no movement. Kittens lived three times longer than old animals of the same size. Frogs, snakes, snails, leeches, supported the privation of air far longer. Ants and mites need air to move. A viper lived sixty hours in a 3½-pint receiver with five-sixths of the air pumped out, as shown by the volume of water which entered the chamber. At the end of thirty-six hours it nimbly put its tongue in and out.

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* Roy. Soc., Phil. Trans., 1670, vol. v.

A bird put in a 4½-pint receiver lived three hours without renewal of the air. If half the air were pumped out, it lived one and a half hours; if three-quarters were removed, it went into convulsions in one and a half minutes. In a very small receiver he killed a mouse in half a minute by one suck of his pump.

He "had a mind to observe whether, when the air was from time to time drawn away, there would not appear some sudden swelling, greater or less, of the body of the animal by the spring and expansion of some air (or Aerial matter) included in the Thorax or the abdomen. Such an inflation, though not great, we thought we observed." In the case of a frog, "her body by degrees was distended." On letting in air, "the abdomen not only subsided, but seemed to have a great cavity in it." A viper's "body and neck grew prodigiously tumid." The heart of an eel in an exhausted vessel continued to beat, grew very tumid, and sent forth little bubbles. It became languid at the end of an hour, but was revived by breathing on the part of the glass where it lay. In the case of a mouse, "we did, by sucking out part of the air, bring him to droop and to appear swelled; and, by letting in the air again, we soon reduced him to his former liveliness."

Boyle studied the volume of air contained in "the pores of water." He pumped out a receiver in which a gudgeon was placed in water until only one-twentieth of the air was left. "The fish, both at his mouth and gills, did for a great while discharge such a quantity of Bubbles as appeared strange, and for about half an hour or more; whenever he rested awhile, new Bubbles would adhere to many parts of his Body (as if they were generated there), especially his Fins and Tayle, so that he would appear almost beset with Bubbles." The fish was affording here points for the formation of bubbles and discharge of the air dissolved in the water. At the end of one and a half hours he was still active, but turned his belly up after a while, and at the end of two and three-quarter hours showed faint signs of life. An oyster in the water kept himself tightly shut, and let no bubbles escape; while from two others, not in the water, foam escaped. Boyle questions whether in common water there is enough air concealed to be of use for fishes. Investigating whipped blood obtained from the butcher, he noted the effect of evacuation—"not so prompt as expected from a liquor so spiritous." After a long attempt he obtained bubbles from it, "the more subtile parts making play across more Viscous." In one experiment the expansion was so much that the contents boiled over the pot, and the blood occupied only one-quarter of the volume of the whole. Hereby Boyle for the first time demonstrated the gases dissolved in the blood—gases which were first collected and analyzed by Magnus in the middle of the nineteenth century. Erasmus Darwin, taking 4 ounces of blood from a vein, found it to foam under the air-pump to ten times its volume. When he tied up a vein, full of blood, between two ligatures, and put it under water in the receiver of the pump, the vein neither swelled nor floated, and therefore Darwin concluded the blood does not really contain an air, but the atmospheric air which gets in when the blood is withdrawn from the vessel and exposed to it —an erroneous conclusion. The explanation lies in the very slow diffusion of air in water, the boiling off of water vapour from the surface of the water, and the consequent shielding of the blood from the vacuum.

Boyle found not only water and blood, but serum, urine, and bile give up air (invisible in their pores) *in vacuo*.* He concluded that animals habituated to rarefaction of the air suffer less; that air can retain its volume, and yet cease to be respirable; that the use of the air is to remove bodily exhalations. If it be too thin or rarefied, the number or size of the aerial particles is too small to be able to carry off the halituous excrements of the blood in such plenty as is requisite. The following speculations of Boyle are of particular interest, in the second he foreshadows the cause of compressed-air illness:

"Death in the receiver was not so much for lack of air as by reason that the air that was pumped out was necessarily succeeded by an etherial substance, which, consisting of parts vehemently agitated, and so very small as without resistance to pass in and out through the very pores of glass, it may well be supposed that a considerable quantity of this restless and subtile matter meeting together in the receiver, with the excessive heat of it, may be quickly able to destroy a little animal, or, at least, make the air too intemperately hot to be fit for respiration."

"Another suspicion we should have entertained concerning the death of our animals—namely, that upon the sudden removal of the wonted pressure of the ambient air, the warm blood of

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* Roy. Soc., Phil. Trans., vii., 1672.

those animals was brought to an effervescence or ebullition; or, at least, so vehemently expanded as to disturb the circulation of the blood, and so disorder the whole economy of the body."

Boyle points out that the bubbles set free in the blood during evacuation may be carried into the smaller vessels, stop the circulation, and so produce disturbances of the most varying nature; and to this, rather than to the mere rarefaction of the air, he ascribes the convulsions and the death of the animal. He suggests that changes of barometric pressure may influence our feelings of health, by altering the volume of the air concealed in the pores of the blood, and so modifying the velocity of the circulation!

He records that he saw a bubble in the aqueous humour of the eye of a viper, which moved from side to side when the animal was convulsed in the rarefied air.

F. Hoppe-Seyler repeated these experiments of Boyle in 1857, and was the first to give a correct explanation of caisson illness deduced from them.* He submitted a rat to rapid diminution of pressure; death occurred at 40 to 50 millimetres Hg. On opening the thorax, bubbles were seen in the vena cava and inside the heart. Similarly, in the case of a cat, 0·3 c.c. of air was found in the right side of the heart, and some bubbles in the left auricle. Hoppe concluded that death was due rather to the obstruction of the circulation by the bubbles than the want of oxygen. He was supported in this supposition by the following experiment: A guinea-pig becomes convulsed at 77 millimetres. He let oxygen into the chamber, and it recovered, but again was convulsed at 75 millimetres; after a second and a third inletting of oxygen, it was still convulsed at 75 millimetres. Therefore, he said, the fall in the oxygen partial pressure was not the cause of the convulsions. In this conclusion he was wrong. Paul Bert repeated the experiments, instantly decompressing to 45 to 120 millimetres a dog, two cats, and three rats, and obtained in none of them the slightest sign of bubbles.† Major Greenwood and the author sought to explain the confliction between the evidence of these distinguished observers. Our experiments mostly gave a negative result, but in one rabbit we found the veins full of bubbles of gas, thus proving the correctness of Boyle's and Hoppe's observations, and yet showing that the

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* Müller's *Archiv*, 1857, pp. 63, 75.

† "La Pression Barométrique," Paris, 1878, p. 93.

negative result obtained by Bert is the usual result. The difference in behaviour of shed blood, which bubbles readily on evacuation, and the blood in the living animal is to be ascribed to the fact that the oxygen in the blood is used up by the tissues ; much of the CO_2 can escape through the lungs during decompression ; so, too, the nitrogen, the volume of which, dissolved at 1 atmosphere, is only 0·96 per cent. Thus in the blood the gas available for bubbling is not great.

Contemporary with Boyle was John Mayow, who, endowed with a wonderful prescience, laid down in unequivocal terms the modern doctrine of respiration. Mayow's nitro-aerial gas is oxygen. He knew that this was used up both in combustion of a candle and in the living activity of animal, and that the animal could live after the candle went out ; "for animals a less aerial spirit is sufficient." "The movements of the lungs help not a little towards sucking in aerial particles which may remain in the flask, and towards transferring them to the blood of the animal."

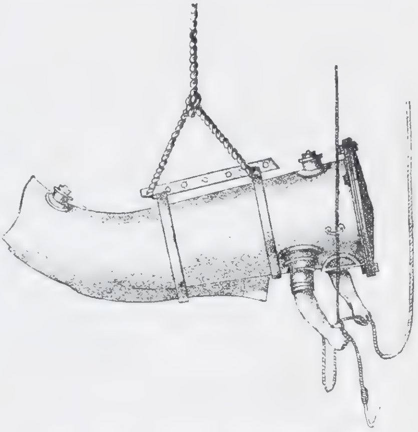

Fig. 8.—Diving Apparatus of Lethbridge.

Mayow died at the age of thirty-six, and his work, gaining little attention from his contemporaries, was forgotten, to be rediscovered by Priestley and by Lavoisier.

John Lethbridge, a Devonshire man, in 1715, being quite reduced and having a large family, turned his thoughts upon some extraordinary methods to retrieve his fortune, and was prepossessed with the idea that it might be practicable to contrive a machine to recover wrecks lost at sea. "The first step I took towards it was going into a hogshead, upon land, bunged up tight, where I stayed half an hour, without communication of air. Then I made a trench near a well at the bottom of my orchard, in order to convey a sufficient quantity of water to cover the hogshead, and then tried how long I could live under water without air-pipes." Finally, a cooper made him an engine "of wainscot, perfectly rounded, about 6 feet in length, about 2½ feet diameter at the head, and about 18 inches diameter at the foot. It is hooped with iron hoops without and within to guard against pressure. There are two holes for the arms, and a glass, about 4 inches diameter and 1¼ inches thick, to look through, which is fixed on the bottom part to be in direct line with the eye. Two air-holes upon the upper part, into one of which air is conveyed by a pair of bellows, both which are stopped with plugs immediately before going down to the bottom. At the foot there is a hole to let the water out sometimes." "I go in with my feet foremost, and when my arms are got through the holes, then the head is put on, which is fastened with screws. I lie straight upon my breast. . . . I can move about 12 feet square at the bottom, where I have staid many times thirty-four minutes. I have been 10 fathoms deep many a hundred times, and I have been 12 fathoms, but with great difficulty." "Mr. Symons came to the Lizard to see my engine, which he liked so well that he desired to adventure with me on some wrecks near Plymouth, where we adventured together without success." Such ingenuity and courage deserved better luck. Let us hope that Mr. Symons supported the large family for some little time while the result of the adventure hung in doubt; or that Lethbridge gained fees from the exhibition of his device.

Adding an air-pump and flexible pipe to Lethbridge's engine, and an exit valve, we have the same invention as the closed diving dress. As the invention stands, it is difficult to think that he could have endured the bloodless condition of his arms and hands so long—bloodless, seeing that his body was exposed to atmospheric pressure in the engine, and his fore-arms to this plus the water pressure. His hands must have been numb and incapable of work. There must, too, have been great risk of the water pressing in round the armholes. Probably a fair amount of water did enter, and, occupying the lower part of the apparatus, partly equalized the air-pressure to that of the surrounding water.

The Venetians at the beginning of the seventeenth century are credited by Figuier with the employment of a diving apparatus—the "cornemuse" or "capuchan"—consisting of a tube which at one end expanded into a helmet covering the head of the diver, and at the other end was fitted to a bellows. An exit-tube led from the helmet and opened on the surface. Fresh air was thus continuously supplied to the diver. Denys Papin (1691) suggested the use of bellows with the diving bell. Edmund Halley (1717) says that for small depths not exceeding 3 fathoms bellows and leaden pipes will answer.* For greater depths efficient air-pumps were lacking. Halley, therefore, invented a device which raised the diving bell into an engine of great practical utility. His bell was constructed of wood covered with lead, and weighted so as to keep it perpendicular. It was 8 feet high, 5 feet diameter at the bottom, and 3 feet diameter at the top. In the roof was placed a lens for admitting light, and a tap for letting out vitiated air. Fresh air was supplied by means of two lead-lined barrels, properly weighted so that they sunk perpendicularly. To a hole in the top of each of these tubs was luted a leathern pipe, the junction being made airtight with oil and wax. The tube was weighted, so that its open end fell below the level of the bottom of the barrel, in which was a bung-hole. The barrels full of air were alternately lowered down to the bell,

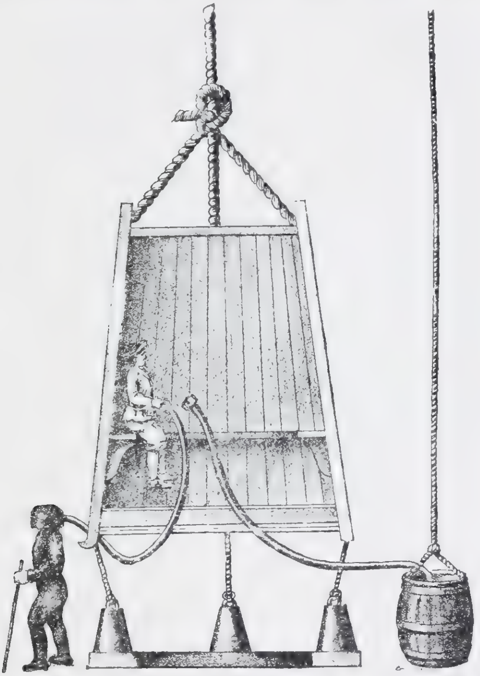

FIG. 9.—THE DIVING BELL OF HALLEY.

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* Roy. Soc., Phil. Trans., 1717.

the attendant in the bell catching hold of the tube, and, drawing the open end upwards into the bell, the air was forced by the pressure of the water from the barrel into the bell. This method was used with such success that Halley and four others remained at the bottom of the sea at a depth of 9 to 10 fathoms for one and a half hours without any inconvenience, and Halley indicates that there were carried out with success submarine works for which the bell was contrived.

The figure indicates how a diver fitted with an open helmet could leave the bell and be supplied with a current of air from the barrel. Halley speaks of the unpleasant rise of temperature in the bell, due, no doubt, to its wooden structure; also of pains in the ears occurring in the compressed air.

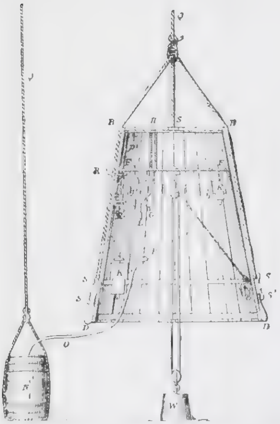

Fig. 10.—The Diving Bell of Spalding.

Charles Spalding (1775) improved on Halley's bell. The upper part of the bell formed a separate watertight chamber, into which water or air could be admitted by cocks, so that the bell could be made to sink or rise at pleasure. A balance-weight was also hung from the centre of the bell by pulley-blocks. By lowering this weight to the bottom the bell could be immediately made to rise. Thus the danger of being capsized by any obstacle met during the descent could be avoided. Spalding and his son were suffocated in their bell in 1788.

Kleingert (1798) constructed an ingenious diving machine by means of which the diver was supplied with air at a pressure corresponding to the depth he was in. The piston is forced in by the pressure of the water, and compressing the air in the reservoir keeps up a steady stream into the helmet. The dress consisted of a metallic cylinder with a domed top, which covered the head and body as far as the hips. A leather jacket with tight-fitting armlets, and drawers with similar leglets, completed the equipment. The capacity of the reservoir was about 50 cubic feet, and the supply of air sufficed for two hours.

Such ingenious but cumbersome kind of apparatus was in use until 1819, when Siebe invented his "open" dress. This consisted of a metal helmet and shoulder-plate attached to a watertight jacket, under which was worn a combination suit reaching to the armpits. The helmet was fitted with an inlet valve, to which a flexible tube was attached. This tube was connected with an air force-pump. The air kept the water from rising in the jacket, and escaped between it and the undergarment. This arrangement gave far greater mobility to the diver, but it necessitated his maintaining the upright position. If he stumbled and fell, the water filled his helmet and drowned him, unless he was quickly brought to the surface. After several years' experiments Siebe overcame the defects of the "open" dress, and invented the "close" dress (1837), the principle of which has since been in general use.

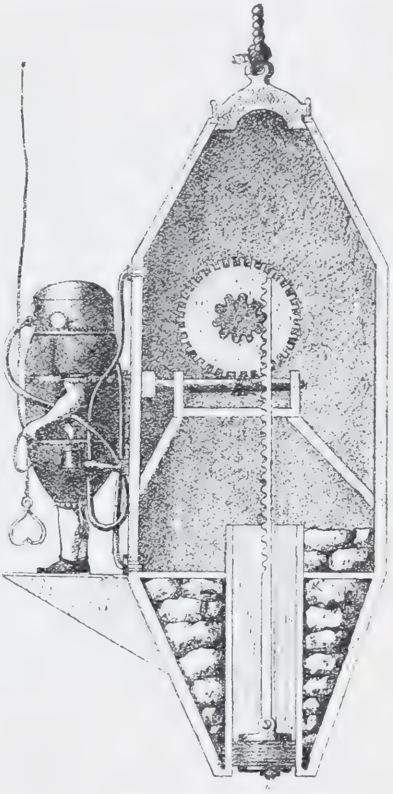

FIG. 11.—THE DIVING APPARATUS OF KLEINGERT.

"Some idea of the importance of the invention may be gathered from the fact that diving apparatus on Siebe's principle is universally used to-day in harbour, dock, pier, and breakwater construction; in the pearl and sponge fisheries; in recovering sunken ships, cargo, and treasure; and that every ship in the British Navy and most foreign navies carries one set or more of diving apparatus for use in case of emergency—cleaning fouled propellers and valves, cleaning and repairing ships' hulls below the water-line, and for recovering lost anchors, chains, torpedoes," etc.*

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* R. H. Davis. Siebe, Gorman and Co.'s "Manual of Diving,"

In 1788 John Smeaton designed a diving bell for repair of Hexham Bridge, and employed a force-pump. The bell was not entirely submerged, and the pump was fixed on the top of it. Smeaton also constructed a square iron bell for use on the Ramsgate Harbour works. "Instead of the usual form of a bell, or of a conical tube of wood sunk by weights (externally applied), this, for convenience, was a square chest of iron, which, being 50 hundredweight, was heavy enough to sink itself; and, being 4½ feet in height, 4½ feet in length, and 3 feet wide, afforded room for two men at a time to work under it. But it was peculiar to this machine that the men therein were supplied with a constant influx of fresh air without any attention of theirs, that necessary article being amply supplied by a forcing air-pump in a boat upon the water's surface."


Fig. 12.—Siebe's First Diving Helmet.

Brize-Fradin (1808) made improvements in the ventilation of diving bells, cooling the compressed air with ice, and introducing caustic soda as an absorbent of the exhaled CO_2.

At the end of the eighteenth century several submarine boats were projected and made trial of. David Bushnell made provision of chambers which could be filled or emptied with water to make the boat rise or sink. Robert Fulton, another American, successfully demonstrated the sinking and rise of his vessel in the Seine (1800). Pazerne (1844) constructed a vessel which was used in Government works at Cherbourg. There was an upper chamber entered by a manhole, and a lower working chamber entered by another manhole, in which eight men at a time could excavate the sea-floor and prepare foundations. By means of poles they could push the vessel along. A pump fixed inside the vessel was employed to fill certain chambers with compressed air, and this was the means used, together with caustic soda, to refresh the exhaled air. The vessel was made to ascend and descend by pumping water in or out of certain other chambers. Pazerne came very near to the invention of the modern caisson.

From 1850 to the present day the modern submarine has been evolved and perfected. The air is not compressed in the submarine, and the length of submergence is fixed by the supply of air enclosed. The submarines are fast growing in size; those of to-day appear giants beside the original Holland boats. The air capacity of the submarine is increasing much faster than the complement of the crew, and thus the possible period of submergence is being increased. When the submarine is on the surface, it is run by oil engines, and by accumulators when submerged. Heavy oil engines are now used in place of petrol. This eliminates the dangers of petrol explosions and poisoning. The water-tanks are emptied and the torpedoes fired by compressed air stored in cylinders at a pressure of 2,000 pounds. There is enough air in the boat to last the crew during a submergence of twelve hours without the CO_2 exceeding 3 to 4 per cent., which is a respirable amount. The air is kept cool by the surrounding water. Fleet-Surgeon Capps has done much to improve the ventilation. When the oil engines are running, the air is drawn through the open hatchway of the conning-tower

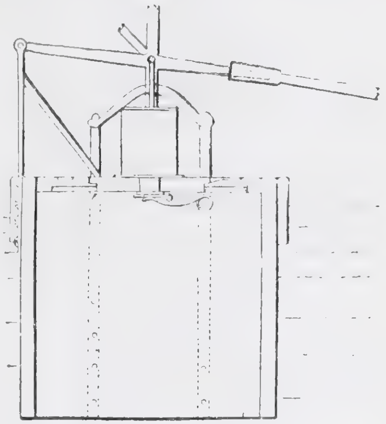

FIG. 13.—THE BELL AND AIR-PUMP OF SMEATON.

to the engine, and the fore and aft part of the vessel are not properly swept out with fresh air.

He suggested that the engine draw its air-supply from pipes opening at the ends of the boat fore and aft, so as to insure the circulation of air in all parts of the boat before submergence. To improve the ventilation during long periods of submergence he suggested the use of a chamber filled with trays of granulated sodium potassium peroxide ($NaKO_3$). A rotatory blower electrically driven is arranged to circulate the air through this chamber, and the exhaled CO_2 is absorbed and oxygen given off by the peroxide.

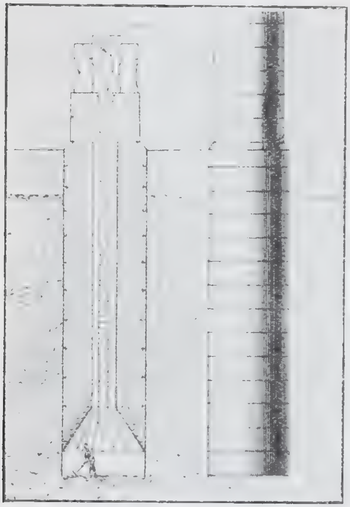

Fig. 14.—The Pneumatic Caisson of Triger.

In the practice firing of torpedoes a cartridge containing calcium phosphate is attached to the torpedo, which produces a flarelight on contact with water. It was found that the poisonous fumes of hydrogen phosphide back-washed from the torpedo-tubes into the submarine, and the use of these lights, therefore, was discontinued. The writer suggests that the calcium phosphide should be covered by a thin layer of some solid readily soluble in water—*e.g.*, sugar. This would delay the contact of the water with the phosphide until after the torpedo had left the tube.

In 1830 Lord Cochrane, the famous Admiral, took out a patent for "an apparatus for compressing atmospheric air (into and retaining the air so compressed) within the interior capacity of subterraneous excavations . . . in order that the additional elasticity given to and maintained in the included air by aid of my apparatus . . . may counteract the tendency of superincumbent water to flow by gravitation into such excavations, . . . and which apparatus at the same time is adapted to allow workmen to carry out their ordinary operations of excavating, sinking, and mining . . . within the space which is filled with compressed air, and also allow workmen ready passage to and from the space into the open air. . . ."

Triger made the first practical application of the same principle (that of the pneumatic caisson) to the sinking of coal-shafts through wet quicksands at Châlons. He forced an iron shaft of about 4½ feet diameter, 25 feet deep, through the quicksand, and constructed an air-lock in this, through which the men could

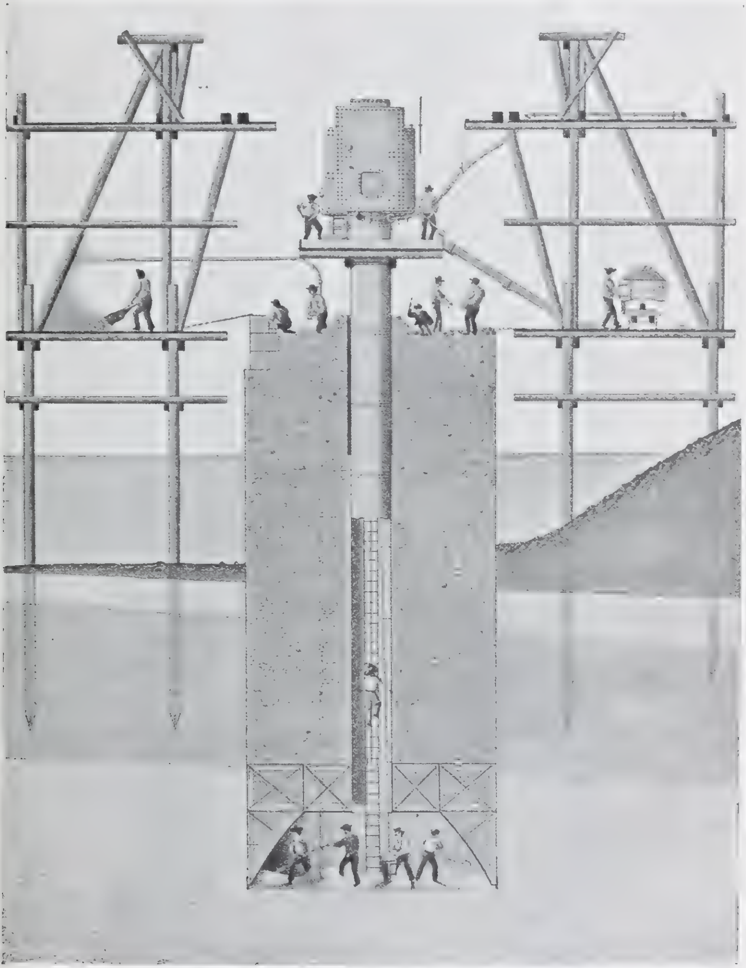

Fig. 15.—A Pneumatic Caisson (Heller, Mager, and von Schrötter).

descend or ascend. Compressed air was driven into the shaft, and forced the water out through the tube. The men were compressed or decompressed in the air-lock by means of the taps HH.

In the same year Hughes and Cubitt employed a pneumatic caisson for building a bridge at Rochester. The caisson was sunk and fixed in its place, and became the foundation of the pile of the bridge. This method of bridge-building came into general use, and all the great bridges and subaqueous works of modern times have been carried out by means of

Fig. 16.—General View of Air-Lock of Caisson.

pneumatic caissons. The caisson and compressed air was also adapted to horizontal tunnelling. D. C. Haskins took out a patent in 1874 to prevent the sudden breaking in of water. Haskins' method was improved by the provision of a steel shield fitted with a cutting edge. This shield is driven forward by hydraulic jacks, and has compartments in it formed of overlapping screens which allow the workmen to get through to the face of the tunnel and hew out the soil. When the soil has been removed sufficiently, the shield is pushed on a step, and a fresh segment of the iron tunnel is built into place and reinforced with concrete. Water is kept out of the work by the use of com-

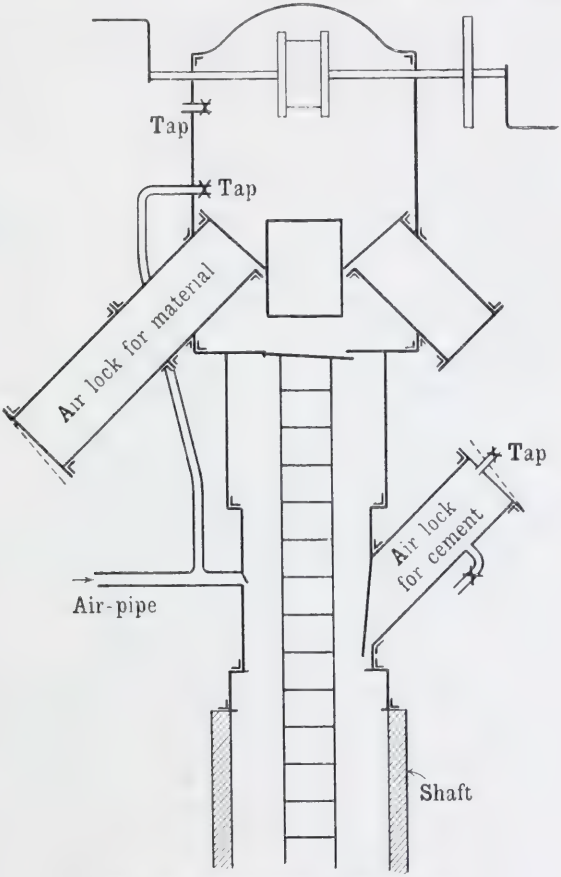

Fig. 17.—Diagram of an Air-Lock.

pressed air, and the men enter and leave the tunnel by a vertical shaft provided with an air-lock for their compression and decompression. All the tunnels made in recent years under the rivers of the great cities of the world have been constructed by this means. Thus, the economic importance of work executed with the aid of compressed air is very great, since the intercommunication of centres of business depend on it. Subaqueous tunnelling, bridge building, shaft sinking, harbour building, the pearl and sponge fisheries, the salving of wrecks, the repair of ships—to execute all these men must work in compressed air.

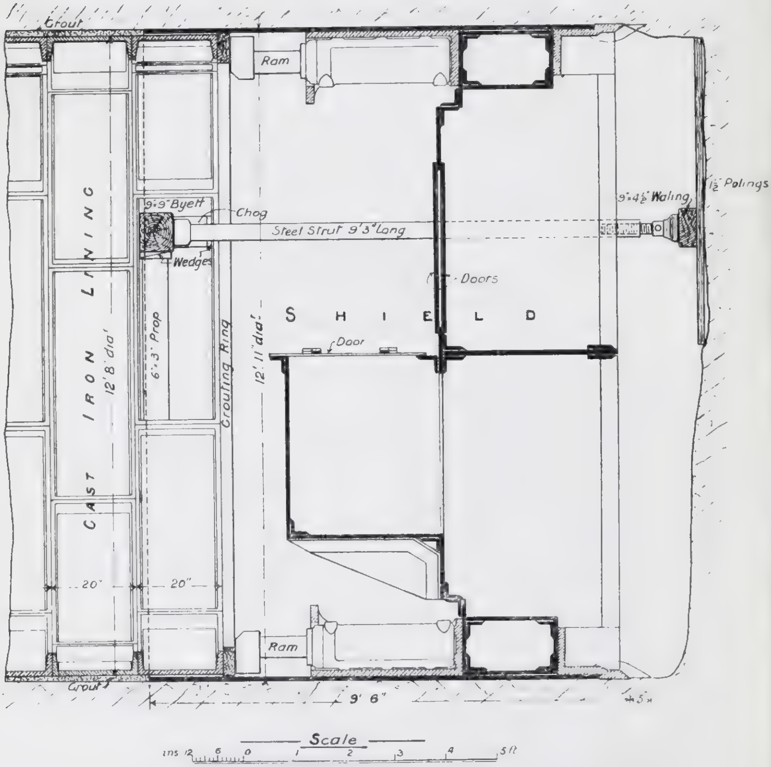

FIG. 18.—PLAN OF SHIELD USED IN WOOLWICH FOOT-TUNNEL (TABOR).

CHAPTER III

THE CONSTRUCTION OF THE DIVING APPARATUS AND ITS USE

A SET of the ordinary diving apparatus consists essentially of seven parts, viz. : (1) A helmet with corselet ; (2) a waterproof diving dress ; (3) a length of flexible air-tube, with metal couplings ; (4) a pair of weighted boots ; (5) a pair of lead weights for breast and back ; (6) a life-line ; (7) an air-pump.

FIG. 19.—DIVING HELMET (SIEBE, GORMAN AND CO.).

The helmet is secured to the corselet by segmental rings, the corselet being clamped water-tightly to the vulcanized rubber collar of the diving dress, which is a combination suit covering the whole body except the hands, which project through elastic cuffs. These make a water-tight joint at the wrists. Air is supplied to the diver through a non-return valve at the back of the helmet by means of a flexible tube connected with the air-pump. The rubber tube is strengthened with embedded steel wire. The air escapes through a spring valve at the side of the helmet, this valve being adjustable by the diver. With this arrangement the pressure of the air in the helmet is always equal to, or slightly greater than, the water pressure at the outlet valve. It is absolutely necessary that this should be so, otherwise the breathing would be instantly stopped, and blood would flow from nose and mouth. There is, in addition, a tap near the front of the helmet, which is used as a supplementary means of letting off excess of air. This tap ("the spitcock") is also used by the diver for taking

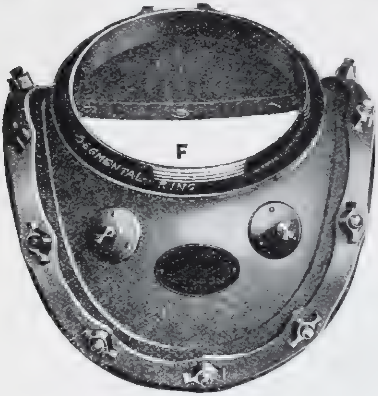

FIG. 20.—CORSELET.

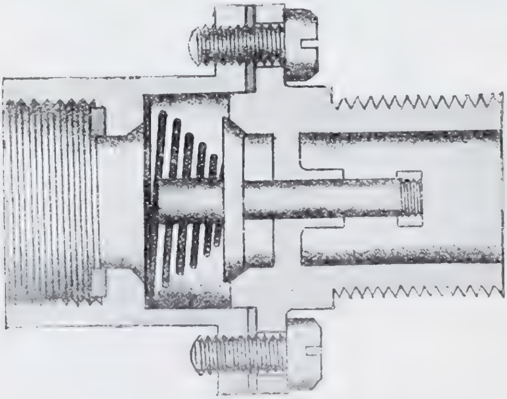

FIG. 21.—INLET VALVE (SIEBE, GORMAN AND CO.).

water into his mouth for the purpose of washing down the moisture condensing on the inner surface of the glass window. To enable the diver to sink and to stand firmly on the bottom, he carries a 40-pound leaden weight on his chest and a similar weight on his back, and 16 pounds of lead on each boot. Altogether the weight of the equipment which he actually wears is about 175 pounds. An ordinary-sized man (*naked*) displaces about 0·075 ton of sea water; a fully equipped diver, with dress *deflated*, about 0·15 ton, and with dress fully inflated, about

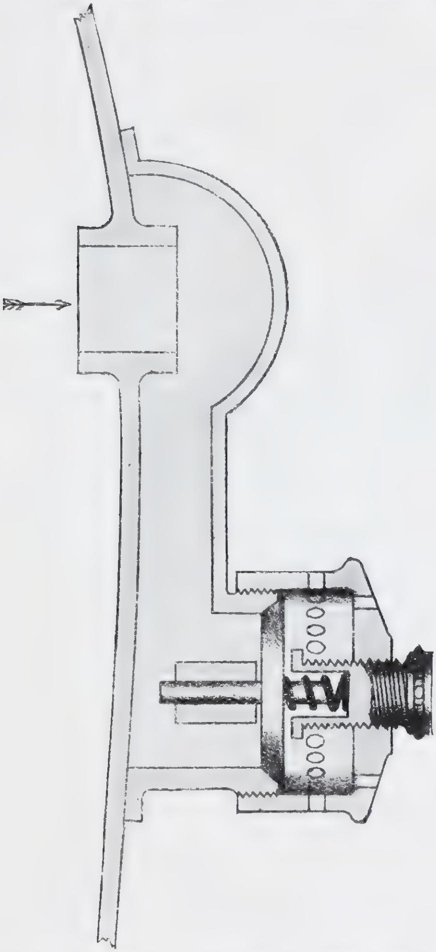

FIG. 22.—OUTLET VALVE (SIEBE, GORMAN AND CO.).

0·31 ton. But if fully inflated he would float, and in so doing would displace exactly the weight of himself and dress, or 343 pounds = 0·153 ton; his displacement would be greater than the equivalent weight of water if entirely submerged. A submerged body displaces in the sea a weight of water equal to the cubic capacity of the body expressed in cubic feet × 64 pounds (the weight of a cubic foot of sea water). Besides the air-pipe, the diver is usually connected with the surface by a signal, or lifeline, in which, in most cases, are embedded telephone wires. He usually descends by a rope (the "shot-rope"), attached to a heavy weight, which has been previously lowered to the bottom, and on reaching the bottom takes with him a line (the "distance line") attached to this weight, so that he can always find the "shot-rope" again.

Fig. 23.—Interior of Helmet (Siebe, Gorman and Co.).

BD, Telephone; A, inlet valve; H, air inlets; C, outlet valve.

As a diver enters the water, the superfluous air in his dress is driven out through the outlet valve by the pressure of the water on his legs and body. The water seems to grip him all round. If the valve were screwed up so that the dress remained inflated, he would not be able to get down. If the valve is freely open, he will feel his breathing rather laboured by the time he gets his valve just under water. The reason of this is that the pressure in his lungs is that of the water at the valve outlet, whereas the pressure on his chest and abdomen is greater by something like a foot of water, or about 70 pounds per square foot. He is thus breathing against pressure, and this hampers the breathing considerably. Haldane studied the effect of varying the position of the valve and the pressure in the helmet. A nozzle was substituted for the valve, and a length of tube attached to this. The valve was placed on the end of the tube. If the valve was held a few inches above the helmet the excess of pressure on the chest was so great that breathing was impossible.

The experiment was very unpleasant, and not free from risk of hæmorrhage into the air passages and over-dilatation of the heart. With the valve at the top of the helmet, breathing was just possible, but laboured. With the valve at the ordinary level, breathing was still an effort, especially during exertion. With the valve at the level of the upper part of the breast-plate, breathing was much easier. The helmet was lifted off the shoulders, and this afforded a much larger space to inspire from. The difficulty with the valve too high up is due largely to the fact that the diver has then to inspire from a small air-space with rigid walls, and only can get enough air during the instroke of the pump. With the valve still lower, the helmet is lifted right off the shoulders, and so much air accumulates in the dress that the diver begins to lose hold on the ground.

Bleeding at the nose, etc., is commonly observed with inexperienced divers, and is due to their not keeping the valve sufficiently closed, especially during exertion, so that the inspiration produces too great a cupping effect on the pulmonary blood-vessels. One of the first things, therefore, that a diver has to learn is to avoid this adverse pressure by adjusting the pressure of the spring on the outlet valve, so that the breathing is always quite free. The spring on the valve at the same time regulates the amount of air in the dress, and therefore the buoyancy of the diver. The diver has to learn to adjust this in accordance with the movements of his head. A practised man can thus slip easily, and without exertion, up or down the shot-rope. The breathing is easiest when the dress is full of air down to the level of the abdomen, but when this is so the diver runs a risk of being "blown up." It will also be readily understood that a horizontal, or nearly horizontal, position is the easiest one for a diver's breathing, and many divers work crawling on the ground. In this position he must open his valve well, but it may happen that too much air gets into the dress. If this air is allowed to get into the legs of the dress, the diver is capsized and blown helplessly to the surface, or he may be caught by a rope or other obstruction, and hung up in a helpless position with his legs upwards, the excess of air being unable to escape at the outlet valve since it is downwards. To avoid this risk, the arrangement for lacing up the legs has been introduced by the Admiralty Committee on Diving. With the legs laced up, the head always comes uppermost if the diver tends to float upwards, hence the excess of air escapes by the valve.

In deep-water diving in the past the divers have suffered from oppression of breathing, and the more so the deeper they have gone. They have universally attributed this to the increase of pressure, and extraordinary dresses have been invented with the idea of holding off the pressure. Thus in the Buchanan-Gordon dress, the head, chest, and hips are enclosed in stout

FIG. 24.—DIVING DRESS WITH LEGS LACED UP (SIEBE, GORMAN AND CO.).

copper, the legs, arms, and belly by metallic springs covered with waterproofing. The arms are fitted with spiral springs and the legs with jointed supports to prevent the water pressure forcing them upwards. To the escape valve is connected a floating pipe, the upper end of which is submerged to any required depth. It will be noted in Fig. 28 that the hands are not enclosed in the dress, and that the entry of water at the wrists is prevented only by the usual rubber cuff. If the dress had ever been used

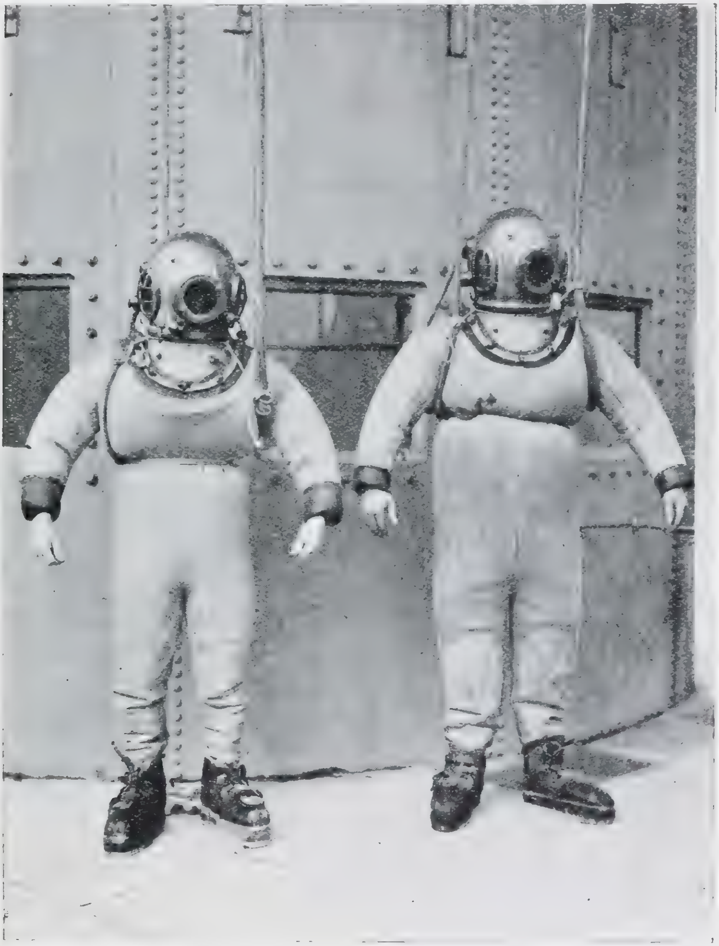

FIG. 25.—DRESSES, LACED AND UNLACED, DISTENDED WITH AIR.

in the way the inventors desired—that is, with a far lower pressure of air in the dress than that of the water outside, the diver would certainly have been drowned. All such contrivances are useless.

No oppression of the breathing was felt by M. Greenwood and the author when they were exposed to +92 and +75 pounds respectively. The breathing was just as free and easy then as at atmospheric pressure. Similarly animals exposed to +10 atmospheres show no change in respiration so long as the ventilation is good and oxygen-poisoning has not ensued. Haldane has done great service in proving that the cause of the oppression which the divers suffer is insufficient ventilation and the increased partial pressure of CO_2 in the helmet.

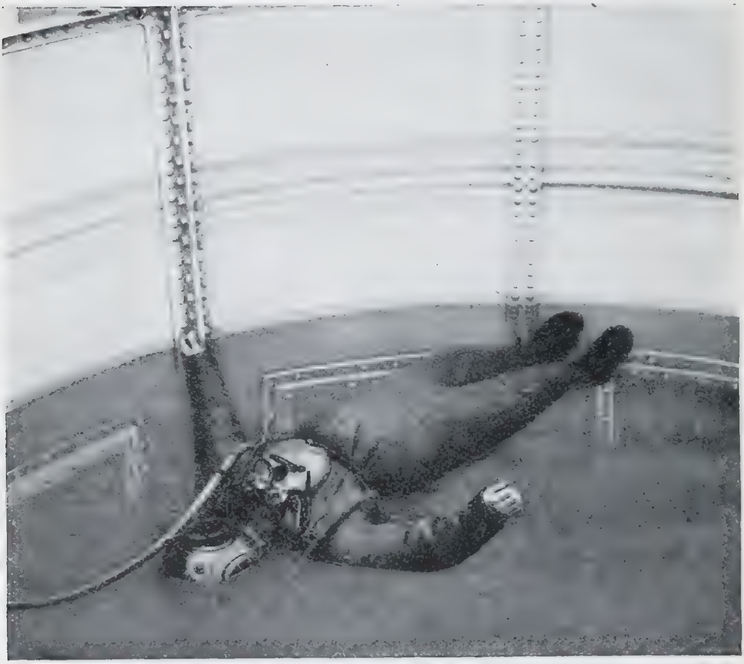

Fig. 26.—Position of Diver in Unlaced Dress after being blown up.

An average adult man breathes about 7½ litres per minute when in a position of perfect rest (roughly ¼ cubic foot). At normal atmospheric pressure each person's breathing is so regulated as to keep the percentage of CO_2 in the air-cells of the lungs at about 5 per cent. of an atmosphere. If the percentage of CO_2 rises very slightly, the breathing deepens, and slackens if the percentage falls, so that the CO_2, or rather the acid concentration in the blood, controls the respiratory centre. During moderate work the amount of CO_2 given off by the lungs is trebled or quadrupled, and the breathing is increased in volume proportionately. With hard work the increase may be tenfold.

FIG. 27.—POSITION OF LACED-UP DIVER AFTER BEING BLOWN UP.

If the inspired air is vitiated by CO_2, the volume breathed is increased in such proportion as, if possible, to keep the percentage of CO_2 in the alveolar air normal. Thus, if the inspired air contain 3 per cent. CO_2, the breathing volume is about doubled, and moderate muscular work in such air causes as much distress of the breathing as very hard work in pure air.* When the atmospheric pressure is altered, it is found that it is no longer the percentage, but the absolute partial pressure of CO_2 which

Fig. 28.—The Buchanan-Gordon Dress.

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* Haldane and Priestley, *Journal of Physiology*, 1905, vol. xxxii., p. 225.

controls the breathing. Thus Haldane and Priestley found that in themselves the percentage of CO_2 in the alveolar air was 6·01 at 765 millimetres Hg and 3·53 at 1,260 millimetres Hg, while the absolute CO_2 pressures corresponding (allowing for the aqueous vapour in the alveolar air) were 5·64 and 5·68 per cent. of an atmosphere—practically the same. M. Greenwood and the author have verified this law up to a pressure of 6 atmospheres. They were compressed in a steel chamber, and took in with them a Haldane gas analysis apparatus, and collected and analyzed the alveolar air at each atmosphere both on the way up and down. It was rather astonishing to observe the percentage of CO_2 fall as the pressure rose, from 5·4 at 1 atmosphere to 0·9 at 6 atmospheres.

SUBJECT, M. G.

Percentage of CO_2 found in Alveolar Air.	Pressure of Gauge in Pounds.	Percentage Multiplied by Pressure in Atmospheres.
5·30	+ 00	5·30
0·90	+ 75	5·40
1·00	+ 60	5·00
1·80	+ 30	5·40
2·70	+ 15	5·40
5·40	+ 00	5·40

SUBJECT, L. H.

Percentage of CO_2 found in Alveolar Air.	Pressure of Gauge in Pounds.	Percentage Multiplied by Pressure in Atmospheres.
4·70	+ 00	4·70
0·90	+ 60	4·50
0·70	+ 75	4·50
0·80 0·95	+ 60	4·75
1·20	+ 45	4·80
1·80	+ 30	5·40
2·50	+ 15	5·00
5·00	+ 00	5·00

Considering the difficulties of *very* exact experiment under the cramped conditions which pertained in the chamber, the variations in ventilation, errors in reading of the pressure-gauge, etc., the results show an astonishingly close agreement with the theoretical values—close enough to make us conclude that no increase or decrease in the pulmonary output of CO_2 occurred, and that the respiratory metabolism was not altered by the increase of barometric pressure. This conclusion is based on the fact that the pulmonary ventilation volume, measured by a Zuntz meter, and reduced to atmospheric pressure, remained practically the same at all the pressures—if the ventilation of the chamber was so arranged as to keep the partial pressure of CO_2 constant. These tables comprise all our results :

SUBJECT, M. G.

Pressure.	Alveolar Percentages of CO_2.					
Lbs.						
0	5·3, 5·4	5·3	5·5	5·7	5·5, 5·7	5·3, 5·4
8	3·3 (5·06) mean	—	—	—	—	—
15	2·3 4·60) mean	—	—	—	—	2·7 (5·4)
16	—	—	—	2·7 (5·58)	2·7 (5·58)	
22		—	2·1 (5·18)	—	—	—
30		—	1·8 (5·40)	—	—	1·8 (5·4)
31	—	—	—	1·8 (5·52)	1·8 (5·52)	—
45	—	—	—	—	—	? 1·3 (5·2)
46	—	—	—	—	? 1·3 (5·30)	—
60	—	—	—	—	—	1·0 (5·0)
61	—	—	—	—	0·9 (4·60)	—
75	—	—	—	—	—	0·9 (5·4)

SUBJECT, L. H.

Positive Pressure.	Alveolar Percentages of CO.				
Lbs.					
0	5·2, 5·3, 4·9	4·9, 5·0	5·15	4·9, 5·0	4·7, 5·0
4	3·5, 4·0 (4·8)	—	—	—	—
9	—	3·35 (5·35)	—	—	—
18	—	2·5 (5·48)	—	—	—
23	—	2·1 (5·30)	—	—	—
17	—	—	2·5 (5·3)	—	—
31	—	81·5 (5·7)	1·7 (5·2)	—	—
14½	—	—	—	2·5 (4·9)	—
30	—	—	—	1·65, 1·7 (5·0)	1·8 (5·4)
44½	—	—	—	1·25, 1·3 (5·1)	—
45	—	—	—	1·3 (5·2)	1·2 (4·8)
52	—	—	—	1·1 (4·9)	—
60	—	—	—	0·95, 1·0 (4·88)	0·9, 0·9 (4·5)
75	—	—	—	—	0·7, 0·8 (4·5)
15	—	—	—	—	2·5 (5·0)

The same law has been found to hold good down to about two-thirds of an atmosphere (Boycott and Haldane). At two-thirds atmosphere the percentage of CO_2 found was $5{\cdot}5 \div \frac{2}{3} = 8{\cdot}25$;

below this pressure O_2 want comes in as a disturbing effect, lactic and other acids are formed, and increase the acid concentration of the blood, so that the respiratory centre is excited to increased action, and the CO_2 washed out of the body. As a result, the partial pressure of CO_2 in the lung is lowered, and in consequence that of O_2 is raised—a compensatory mechanism.

When the centre comes under the influence of an abnormally low partial pressure of CO_2, it no longer works smoothly, but periodically—Cheyne-Stokes respiration.

It follows that the effects on a diver of a given percentage of CO_2 in his helmet vary with the depth. If air containing 5 per cent. CO_2 produced great panting at 1 atmosphere, air containing $\frac{5}{7\cdot4}=0\cdot68$ per cent. will produce the same degree of panting at 35 fathoms. The following table gives the results of breathing in and out of a large bottle at different pressures, the volume of the breathing being recorded (Haldane):

Subject.	Period of Breathing.	Atmospheres Absolute.	Percentage of CO_2 in Bottle at End of Experiment.	Partial Pressure of CO_2.	Increase in Volume of Air Breathed.
	Minutes.				
D. ..	3½	1·0	5·00	5·10	× 2·4
	4	3·7	1·60	5·92	× 2·2
C. ..	3½	1·0	6·22	6·22	× 2·9
	3½	3·7	1·64	6·07	× 2·3

They show that the effect of CO_2 on the breathing depends on the partial pressure, and not on the percentage of this gas in the air breathed. It follows from this that *whatever the pressure a diver is under he requires the same volume of air measured at that pressure.* Thus, at 35 fathoms, where the absolute pressure is 7·4 atmospheres, he requires 7·4 times the volume of air measured at ordinary atmospheric pressure as he requires at the surface.

At 2 atm., or 33 ft., the air-supply must be doubled.
,, 3 ,, 66 ,, ,, ,, trebled.
,, 4 ,, 99 ,, ,, ,, 4 times.
,, 5 ,, 132 ,, ,, ,, 5 ,,
,, 6 ,, 165 ,, ,, ,, 6 ,,
,, 7 ,, 198 ,, ,, ,, 7 ,,
,, 8 ,, 231 ,, ,, ,, 8 ,,
,, 9 ,, 264 ,, ,, ,, 9 ,,
,, 10 ,, 297 ,, ,, ,, 10 ,,

As in the past this law has not been realized, and the same amount or less of air (owing to leakage and hard work of pumping) has been sent down at great depths, the divers have been poisoned by CO_2, and rendered unable to work, and in some cases unconscious.

Haldane and Priestley found that, with a pressure of 2 per cent. of an atmosphere of CO_2 in the inspired air the pulmonary ventilation was increased 50 per cent.; with 3 per cent., about 100 per cent.; with 4 per cent., about 200 per cent.; with 5 per cent., about 300 per cent.; and with 6 per cent., about 500 per cent. With the last panting is severe, while with 3 per cent. it is unnoticed until muscular work is done, when the panting is increased 100 per cent. more than usual. With more than 6 per cent. the distress is very great, and headache, flushing, and sweating occur. With more than 10 per cent. there occurs loss of consciousness after a time, but no immediate danger to life. Even 25 per cent. takes a long time to kill animals.

FIG. 29.—METHOD OF COLLECTING SAMPLE OF AIR IN HELMET.

If muscular work is being done and the diver is panting for breath from CO_2 excess, fatigue of the respiratory and circulatory mechanism will ensue much quicker. Owing to the panting and struggling more CO_2 is produced, and a vicious circle arises. The diver never suffers from want of oxygen when under pressure, because the CO_2 pressure must rise to a point where it produces its effects before the oxygen can fall to a low level.

Unpractised divers produce much more CO_2 than trained men, owing to the strain of the unaccustomed position, and the fact that they do not ease their breathing by regulating the exit valve properly.

An important series of observations were made by Haldane, and published in the report of the Admiralty Committee on Deep Sea Diving, 1907. The divers took down receivers of stout glass, provided with three-way taps at each end, and marked by knobs of glass, the number of which could easily be counted by the diver. The receiver was attached by a rubber tube to the "spitcock," and held above the level of the outlet valve, so that the air should blow out freely. In the case of samples taken from deep water the excess of pressure in the receiver was relieved when the diver was half-way up by opening the tap at one end for a moment or two. The "work" samples had to be taken without delay, and these were collected in 2-ounce bottles simply inverted over the tap. Each bottle was closed by a perforated cork, through which passed a short glass tube, to which a piece of rubber tube was attached, the latter having a longitudinal slit in it, and being closed by a solid glass rod. The excess of air escaped through the slit as the diver ascended, and at the surface he pushed home the glass rod and closed up the slit. The production of CO_2 per minute by the diver could be calculated from the analyses of the helmet air, whenever the delivery of the pumps allowing for leakage was known.

FIG. 30.—METHOD OF CARRYING OUT WORK TEST FOR DIVERS.

The tables published by the Admiralty Committee show that the partial pressure of CO_2 in the helmet varied from 0·18 to 10·0 per cent. of an atmosphere. "The sample showing the latter very high pressure was taken under great difficulties by Inspector Watkins just before signalling for more air, and when he was probably on the verge of losing consciousness." His distress was entirely due to the inadequate air-supply—about 1·6 cubic feet per minute, measured at the surface, and less than 0·4 cubic feet as it reached him. From the statements of the divers the general inference was drawn that inability to make any considerable or continued exertion arose when the CO_2 pressure exceeded 4 per cent. of an atmosphere. Thus, at a depth of 139 feet, and with a CO_2 pressure of 4·28 per cent. of an atmosphere, Lieut. Damant was unable to continue for more than eight minutes the exertion of lifting a weight of 56 pounds about 7 feet per minute. The work test was done by the following means : A spar, carrying a block and pulley, was rigged up from the deck of the vessel. "Over the pulley a rope was passed, with a 56-pound weight attached at one end near the surface, the other end being rove through a second pulley attached to a 2-hundredweight sinker on the bottom, so that the diver could stand upon the sinker and haul on the rope. An observer on deck counted the number of times the diver could lift up the 56-pound weight and the height of each lift, a toggle being attached to the rope to facilitate observations."

When the CO_2 pressure was well under 3 per cent. of an atmosphere, heavy exertion could be continued for long periods, and even at the extreme depth of 210 feet the divers were comfortable with a CO_2 pressure of less than 4 per cent.

"The average resting production of CO_2 by Damant and Catto in the experimental tank was 0·014 and 0·013 cubit feet per minute respectively. On the sea-bottom where the tide was running the amount rose to 0·022 and 0·016. As both divers are spare, weighing only about 11 stone, their normal resting production was probably only 0·01 cubic feet, and this production may be assumed to be doubled when resting on the sea-bottom, and even quadrupled when a tide is running and exertion is required to maintain a footing." At a depth of 210 feet Damant's "resting" production of CO_2 was the same as in the tank. He was breathing in 7·3 times as much oxygen as usual, but the oxidation processes of his body were not increased in the least degree. During work the production of CO_2 rose to 0·04 to 0·06 cubic feet per minute, and once to 0·079 cubic feet per minute, when Catto had to struggle to free himself from mud.

In calculating the proper air-supply for a diver, allowance must be made for fairly hard work. He "may have to struggle with tide and mud, or, when he is foul, often in darkness." The work, being unusual, will be done uneconomically. If he has also to struggle for breath owing to a high pressure of CO_2, he may easily become incapacitated and lose his life.

To keep the CO_2 down to 3 per cent., a diver at rest ought to have $0{\cdot}019 \times \frac{100}{3} = 0{\cdot}63$ cubic feet per minute, and during work $0{\cdot}045 \times \frac{100}{3} = 1{\cdot}5$ cubic feet per minute. He must have this volume of air at whatever pressure he may be. An ampler supply would be still better, for 3 per cent. will limit his power to do *hard* work. There is no danger in breathing 3 per cent. of CO_2, and the supposed danger of organic impurity in the exhaled air does not exist.

In calculating the number of cylinders required to give the right amount of ventilation, account must be taken of a certain amount of leakage which is inevitable in the air-pumps.

The service air-pumps made by Messrs. Siebe, Gorman and Co. are fitted with pistons provided with leather caps, carefully fitted, and furnished with steel springs to keep the leathers closely applied to the cylinders. The Admiralty Committee found that the leakage is about 10 per cent. at 100 feet, and 24 per cent. at 200 feet, and point out that there are certain unavoidable causes of loss, for a small volume of highly compressed air must be left in the cylinder at the end of each stroke; and as the piston and cylinder are heated more or less, the incoming air will be warmed, and will take up some of the condensed moisture and expand, with a consequent diminution in the mass of air delivered by the next stroke.

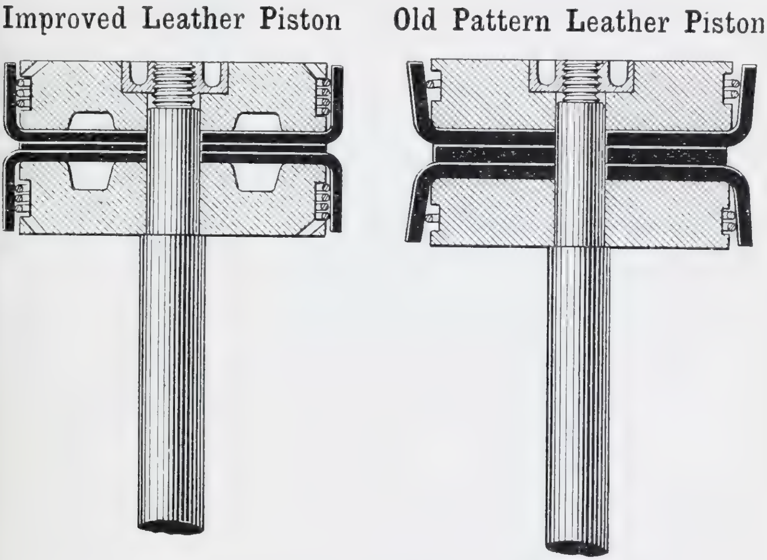

Fig. 31.—Pistons of Diving Pumps (Siebe, Gorman and Co.).

Assuming this amount of leakage as unavoidable, the Committee set out the required ventilation thus :

Depth in Feet.	Cubic Feet of Air per Minute.	Number of Cylinders Required.	Record of Pumps per Minute.	Work in Compressing. Foot-Pounds per Minute.	Number of Men needed for Each Spell.
0	01·5	1	15	—	—
16	02·2	1	22	1,927	2
33	03·0	1	30	4,440	2
66	04·5	2	22	10,500	4
99	06·0	2	33	17,600	6
132	07·5	4	21	25,600	8
165	09·0	4	27	34,000	12
198	10·5	6	23	43,000	18
231	12·0	6	25	53,000	18

Provision ought to be made to let the diver have at least a third more air than this if he gets into difficulties with mud, tide, or a foul. For instance, at 30 fathoms Catto accidentally got foul of the coils of a wire hawser. "The two pumps supplying him with air were meanwhile, owing to the men being tired, only going at twenty-four revolutions per minute, so that the air-supply was about 8 cubic feet per minute, which was not much short of 9·7, the calculated quantity. Although he was comfortable enough with this air-supply as long as all went well, he found it quite insufficient when he was exerting himself to get free, and was so much affected by the CO_2 that before he had freed himself, after a struggle of twenty minutes with the coils of the hawser in soft mud and pitch darkness, he had begun to feel in danger of losing consciousness unless he stopped to rest."

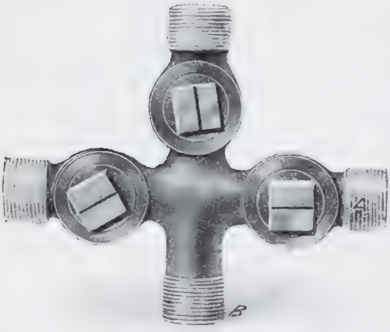

Fig. 32.—Fourway Junction for joining up Pumps (Siebe, Gorman and Co.).

A four-way junction is used for connecting up two or more pumps for deep-water work. "If, when using this junction, the diver being under water, it is desired to take off one of the pumps, the tap on the connection to which that pump is joined up must first be shut. When putting on an additional pump, it must be hove round, delivering its air against the shut tap till its gauge shows the same pressure as the other pumps heaving for the diver; after this the tap may be opened. The greatest caution must be exercised in opening taps on the junction when the diver is down." Should the air be allowed to escape, the diver would get a dangerous squeeze.

It is very necessary that the pumps should be tested. To test the real efficiency the delivery pipe is connected to a length of hose which can be compressed by a screw clamp. The hose is connected in turn to a dry gas-meter of "thirty lights" capacity. To test the pump the number of revolutions required to deliver 10 cubic feet is counted when (1) the clamp is opened, (2) screwed up (*a*) till the gauge indicates a pressure of 100 feet of water, (*b*) 200 feet of water. In the absence of a meter the efficiency can be tested by connecting the pump with a reservoir of known capacity—*e.g.*, a compressed gas cylinder. The number of revolutions are counted which are required to raise the pressure 15, 30, 45, 60, 75 pounds. With a single cylinder 10 revolutions ought to yield 1 cubic foot, if there is no leakage. Thus, 100 revolutions ought to yield 10 cubic feet, and if 150 were required, the leak would be 33 per cent.; if 200, 50 per cent.; if 300, 67 per cent. The valves of old pumps, if not properly looked after, may leak 30 to 50 per cent. at depths of 100 to 200 feet—hence the difficulty in the past of deep-water work.

FIG. 33.—TESTING A PUMP BY METER AND SCREW CLAMP.

The work required to heave round the pumps to the necessary extent increases with the depth much more rapidly than the pressure. At 210 feet thirty-six men working very hard in alternate five-minute spells of rest and work were scarcely able to keep up the proper air-supply. Long handles were supplied to allow three men on each side of the pump. For deep work an air-pump, worked by a steam, gas, or oil engine, is obviously required, and a steel reservoir can then be employed to keep up a continuous stream of air.

CHAPTER IV

THE NATURE OF CAISSON SICKNESS

Attention was first drawn to " caisson disease," or compressed-air sickness, in the middle of last century, when Triger applied the use of the pneumatic caisson to the sinking of coal-shafts through the wet soil at Châlons. In all the great compressed-air works from first to last the men have suffered from illness and loss of life caused by the compressed air.

examples

Reporting on his first caisson, Triger* recorded that the voice becomes nasal in character, and the more so the higher the pressure. It is not possible to whistle at 3 atmospheres. The workmen find themselves less out of breath after climbing a ladder in compressed air. A man who was deaf heard much better in compressed air. Playing a violin, Triger found in the compressed air the sound lost half its intensity.

Treuessart,† appointed to investigate the physiological effects, entered Triger's caisson with some trepidation for the first time, thinking of the 32,000 kilogrammes extra pressure his body would bear, " enough to frighten the shoulders of the strongest." He found no change in the functions of nutrition, circulation, respiration. The workers, he reported, climb with greater ease, but are more fatigued by work in compressed air. He attributed this to the excessive humidity of the caisson, which hinders the insensible perspiration and provokes sweating. He put down to this cause the acute articular pains from which some of the workers suffered a few hours after leaving the caisson.

Two workers who had laboured seven hours in the caisson suffered from very acute pain ; in one the pain was located in the left arm, and in the other in the knees and left shoulder. The pains were relieved by massage.

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* Triger, *Compte rendus. Acad. des Sciences*, 1841, tome xiii., p. 884.

† Cit. after Bert.

CAISSON SICKNESS IN SOME OF THE CHIEF WORKS.

Date.	Place.	Maximal Pressure.	Cases of Illness.	Deaths.	Period of Decompression for Maximal Pressure.	Reported by—
1839	Douchy mines shaft-sinking	+ 2·5 atm.	63 (many severe)	2	30 min.	Pol and Watelle.
1840	Strépy-Braquegnies shaft	+ 2·7 atm.	All except one worker suffered	—	—	Bouhy.
1859	Kehl, bridge over Rhine	—	133	1	—	François.
1862	Bayonne, bridge over Adour	+ 3·5 atm.	90 per cent. of men suffered	1	12 min.	Limousin.
1870	St. Louis, bridge over Mississippi	+ 50 lbs.	129 (56 paralysis) Shift reduced to 1-2 hours, with good results	14	—	Jaminet and Clark.
1873	Brooklyn Bridge	+ 34 lbs.	110 (in four months)	3	A few minutes	A. H. Smith.
1883	Cubsac Bridge	+ 7·6 atm.	104 (16 severe); recompression chamber employed	—	3·18 min.	Gerard.
1885	Bridge over Eider	+ 2·6 atm. (5·30 sec. decompression	380 cases of illness in 140 men	—	2 min. 5·30 sec.	v. Heller.
1885	Hudson Tunnel	+ 35 lbs.)	1 man out of 50 workers died per month	9	Rapid	E. W. Moir.
1889	Wyoming	+ 40-42 lbs. (10 min.)	22 (10 per cent. of the old, and 35 per cent. of the new, workers); 5 out of 41 workers at 42 lbs.	—	10 min.	C. P. Knapp.
1890	Bridge over Danube (Fetesti-Cernaveda)	+ 32·5 min.	154 (55 severe)	4	—	E. Gärtner.
1895	Nüssdorf Works, Danube	+ 2·5 atm.	320 cases among 675 workers	2	35* min.	V. Schrötter.
1905	Westeligke Viaduct, Amsterdam	+ 2 atm.	63 cases in 134 workers	—	32½ min.	

* Probably often accelerated.

MM. Pol and Watelle * gave to the world the first important account of the illness resulting from compressed air. In the sinking of a mine-shaft at Lourches a pressure of 4¼ atmospheres absolute was reached. Compression was made in 15 minutes, and decompression in 30 minutes. The men worked two shifts a day each of four hours.

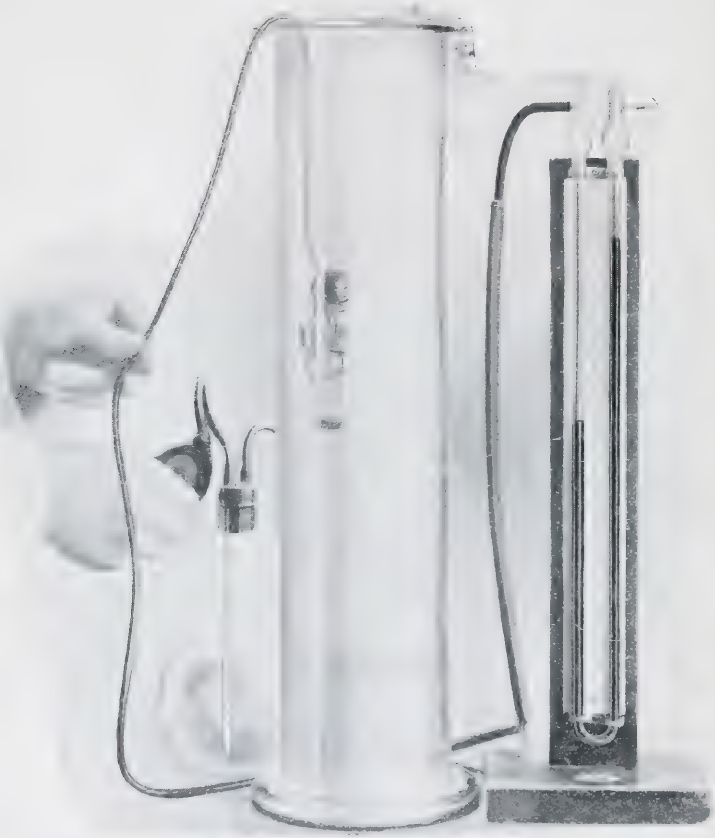

Fig. 34.—Schema for demonstrating that the Pressure in the Diver's Helmet must equal the Pressure of the Water.

A hole is made in the back of the helmet of the toy diver, and air is pumped through the diver's helmet by the syringe bulb. The pressure is indicated by the manometer, and this rises as the diver sinks.

The physiologic effects observed were pain in the tympanic

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* *Ann. d'Hygiene Publique* and *De Méd. Légale*, second series, 1854, tome i., pp. 241-279. Cit. after Bert.

membrane, diminution in frequency of respiration and in amplitude of thoracic expansion, slowing of the pulse (70 to 55), augmentation in secretion of urine, sense of muscular resistance. The unwonted density of the atmospheres seemed to make progression less easy. Inability to whistle or whisper. During decompression the men feel the cold, and the pulse accelerates—*e.g.*, to 85.

Pathologic effects were numerous. Out of 64 workers, 47 endured the work and remained more or less well, 25 were discharged, 14 had slight affections, 16 more or less severe, 2 died.

An asthmatic and a "chloro-anæmic," who had several attacks of hæmoptysis, were relieved while in the compressed air. There was no risk in going in or staying in the caisson—*on ne paie qu'en sortant.*

The young men (18 to 26) were far more immune to the ill-effects than the older men. Of the 25 discharged, 19 were more than forty, 5 more than thirty, and 1 twenty-eight years old.

The following types of cases were recorded :

I. Asthmatic subject was taken after decompression with a great feeling of oppression and reaction of the circulatory system.

II., III., IV. Embarrassed respiration, loss of appetite and indigestion, pain in the limbs.

V. No trouble up to 3 atmospheres after working at the higher pressure. Muscular pains and cramp, general numbness, vomiting. One day, after leaving the caisson, became ill while eating his dinner, lost consciousness, pulse full and frequent, face congested, respiration short and stertorous, bronchial sounds and mucous râles heard, complete muscular resolution. Bled, purged, and blistered. Recovered after four hours. Well in three days' time.

VI. After 4¼ atmospheres. One evening in bed seized with muscular pains, tetanic contractions ; skin cold, pulse small and slow, anxious respiration. Baths at 32° C. made the pains worse. Massage of good effect. Well next day.

VII. Cerebral symptoms, like the coma of a drunkard, dull and stuttering. Respiration and pulse quickened. Pupils dilated. Diplopia, tendency to reel ; deafness on one side persisted.

VIII. Pulse accelerated from 58 to 130.

XVIII. Severe pain in chest and limbs, respiratory troubles, increasing with the rise of pressure.

Discharged, but went down and worked without permission. Left the air-lock with the others and went to wash, fell unconscious, and died in fifteen minutes. The autopsy showed only congestion of liver, spleen, kidneys.

XIX. Violent oppression, with dulness and bronchophony,

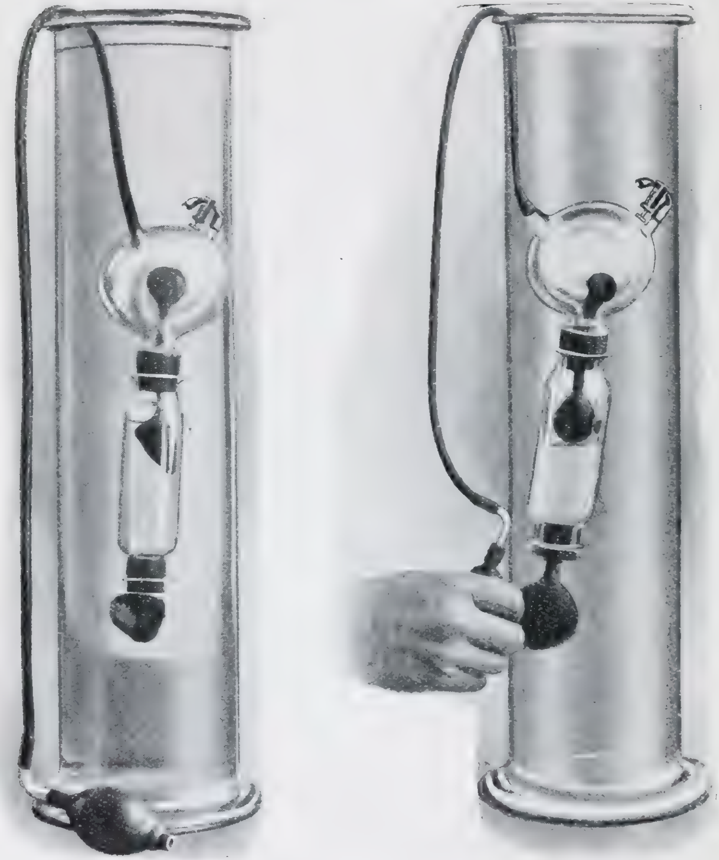

FIG. 35.—SCHEMA FOR DEMONSTRATING THE ACTION OF THE DIVING DRESS.

If the pump is not worked, the pressure of the water squeezes the lowest bag (the abdomen) and the middle bag (the lungs), and blows out the top bag (the head). By working the pump the conditions can be restored to the normal—*i.e.*, the bags become of the same size as when the model is taken out of the water.

rapid pulse, cold skin, continual cough, clonic spasms of limbs; better after five hours.

Another day the same result, with dilatation of the pupil, resolution of the muscles, subdelirium, and coma. Bled. Blood issuing from vein appeared red. Recovered.

XX. Pains and tetanic spasms, remained deaf on one side, and sight enfeebled.

XXI. Vision troubled and doubled, hearing lost, respiration *gênée*, frequent cough, pulse hard and galloping. Red blood flowed on opening vein. Cured.

XXII., XXIII. Pains in head, vertigo, cramps.

Pol and Watelle drew the following important conclusions, which are in every point correct. It is strange how these have been neglected.

Compression up to 4¼ atmospheres is not in itself to be feared. It is endured without any trouble, and infinitely better than rarefaction to a far less proportional degree. The return to the normal pressure is alone to be dreaded; the risk of this *is proportional to the period and degree of compression, and to the rapidity of decompression. It is necessary to make the last much slower.* There is every justification for hoping that recompression is a prompt and certain means of effecting relief from caisson illness, followed by careful decompression.

Bouhy* recorded that at the mine at Strépy-Bracquegnies (Belgium) the workers who were seized with severe pains were relieved by going back to work in the compressed air.

We see, then, that from the earliest use of pneumatic caissons recompression was recognized as the sovereign cure.

Le Roy de Méricourt† published the first report of medical interest concerning the illness of sponge-divers. He mentions the frequent occurrence of paraplegia, and suggests that the diver ought to spend a minute for every metre in coming up, and that the time spent on the bottom of the sea should be in inverse proportion to the depth.

A. Gal,‡ in 1872, gave an exact account of cases he observed among the Græcian sponge-divers. Of particular interest is the case of a diver who was working with four others at a depth of 28 metres. The boat riding round on its anchor entangled the pipes and signal-lines of the divers with the chain. The signals were in consequence misunderstood, and this particular diver

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* *Ann. des Tran. Publ. de Belgique*, 1848, t. vii. Cit. after Bert.

† *Bull. de l'Académie de Méd.*, 1868, xxxiii. *Ann. d'Hygiène Publ. et de Méd. Légale*, 1869, second series, xxxi. Cit. after v. Schrötter.

‡ "Des Dangers du Travail dans l'Air Comprimé et des Moyens. de les Prevénir Thèses de Montpellier," 1872. Cit. after Bert.

was three times pulled about 10 metres and let drop again suddenly, to the detriment of his ears. He was exposed in all for one hour to 3·8 atmospheres absolute.

Next day he worked on board ship and did no diving. In the evening he was doubled up with most severe pain, " as if his chest and belly were being torn open." He was unable to void his urine ; his penis was semi-erect. The day after he tried to get up, but his limbs failed to support him. The paraplegia was only temporary. The patient was *très indocile*, and refused to be properly purged. Gal, unbeknown to him, put 24 centigrammes of calomel into his milk. This effected the complete cure.

Another case was that of Nicolas Theodorus, a man of great size and enormous corpulence. He had dived during three months off Crete without accident, but one day, fifteen minutes after coming up from 37 metres, was seized with paralysis of the lower limbs. He had been down half an hour, and, according to the dangerous custom of the Greeks, had been " blown up "—*i.e.*, decompressed in three to four seconds. He had taken off his clothes and was resting when taken unwell ; he found he could neither feel nor move his limbs. Gal was 100 miles away, and the unfortunate man was taken to the nearest place, where there was an ignorant Italian doctor, who only gave a purge, and did nothing to relieve the paralysis of the bladder. The poor fellow died from retention of urine after eight days of the greatest suffering.

He describes two cases where the divers were " blown up " from 40 to 45 metres, and reached the boat perfectly well, and then suddenly died. One complained of vertigo, fell down and died ; the other, after chatting for fifteen minutes, was seized suddenly with great pain, and almost immediately lost consciousness, and quickly died.

Another, after thirty minutes at over 30 metres (his second dive that day), went to rest, and was found an hour later completely paralyzed, unconscious ; the skin was blue and in a cold sweat. He died in twenty-four hours.

Still another unfortunate was seized, half an hour after coming up from 35 to 40 metres, with violent pain in the epigastrium and complete paralysis, motor and sensory, of the lower limbs, bladder, and rectum. Three days he went without relief of bladder or bowels. A month later he had a huge bedsore on the lower part of his back, laying bare the sacrum and one trochanter ; there were ulcers also on the feet. He suffered from atrocious pains in the belly and constant constipation. He died of marasmus in three months.

A similar case of paraplegia went five days (dreadfully suffering) before he reached port, and got the distension of his bladder relieved. With care he recovered completely in three months' time. Two other similar cases recovered, one in a month and the other in twenty days.

Gal says that the divers are made thin by the work, and get anæmic-looking after many days' work, with increased tendency to suffer from compressed-air illness, so that almost all have pain in the limbs, etc.

Some of his cases felt oppression and ill while at the bottom, and, signalling to be "blown up," became unconscious and paralyzed after reaching the surface; one such had been previously working five hours at the bottom. These divers probably suffered from excess of CO_2 in the helmet.

In a case reported by a Dr. Cotseneopoulos to Gal, an autopsy followed death from paraplegia and bedsores. The spinal cord was found to be softened and diffluent in the upper thoracic and in the lumbar regions. There was blood extravasated between the dura and cord in the lumbar region, and surrounding the cauda equina. "Mais comment se produisit cette inflammation de la moelle ? Est-ce par des hémorrhagies capillaires ? Est-ce par dilatation des capillaires par les gaz et de suite par altération de nutrition (ramollissement) ? Les examen, microscopiques sur des hommes ou sur des animaux pourrant élucider cette question."

In 1890 Catsaras published a monograph rich in first-hand observations on the illnesses of Græcian divers. Among these we note the case of a diver, aged thirty-five, who had worked five months without accident. One day, after a seventh dive (depth, 39 metres; duration, ten minutes; decompression, one minute), he became unconscious directly after his helmet had been taken off. After ten hours he came to, and although he could understand, could neither speak a word or recognize objects. Soon after the man was suddenly taken with paralysis of the right arm and leg. On the right half of the chest there was a swelling, and on rubbing this a friction sound was heard—no doubt due to bubbles of gas in the subcutaneous fat. After fourteen hours he recovered his speech, and after a night's sleep the paralysis had gone; only the swelling remained. Five years later he again became unconscious after the sixth dive on the day, but recovered in three hours' time. In another four years' time, after his first dive, he was seized with complete paralysis of the legs, and loss of consciousness followed. After three hours the paralysis became better, so that he could stand with the help of sticks. The sensibility was depressed, and he could neither go to stool or void his urine. In another four hours' time he was completely recovered, and he went to work next morning. A year later, after his third dive (39 metres, eight minutes' duration, one minute decompression) he suddenly lost consciousness for fifteen minutes. Paresis of the left leg followed, which slowly became better. Three months later the leg was found to become tired quickly, and to show tremor when tired. The reflexes were increased in this leg; often of a sudden it was flexed or extended.

Another diver, after working five minutes at 40·6 metres, was "blown up" in three to four seconds. A few minutes after he said he felt unwell, and was then seized with convulsions on the left side of his body. The fits began with flexion of the left arm at wrist and elbow and pronation of the forearm. After some minutes, rhythmic clonic spasms began, the head being bent to the left, and the left side of the face convulsed with a quick rhythm. The left leg then followed suit, and passed into extensor spasm. The spasms passed into tremors, and the fit ended. In several of the fits the rigidity and tremor passed to the right side, and the man lost consciousness. Temporary paralysis of the left arm and leg followed each fit. The pulse rose to 130, and the temperature to 41° C. Twenty such fits occurred while Catsaras watched him; how many altogether was unrecorded. In a few hours' time the fits ceased, and three hours later the paresis vanished, and the man recovered completely.

An interesting case was that of a diver who thirteen times was seized with temporary hemiplegia, seven times on the left and eight times on the right side, lasting half an hour to two hours, and followed by shooting pains in the affected limbs. There was oppression and pain in the stomach, and congestion of and a burning feeling in the eyes, but no anæsthesia or affection of the bladder or rectum. The man was always affected after the sixth dive (depth, 32½ to 34 metres; duration, fifteen minutes; decompression, one minute), and after restricting himself to not more than five dives in a day had no further trouble.

A diver was down ten minutes at 32 metres when his air-pipe ruptured. He said afterwards that he felt as if his dress was pressed together. He was quickly pulled on board, and was found unconscious, muttering, and bleeding from the nose and ear. He was undressed with difficulty, because his body was swelling! His head swelled and lost shape. In particular his eyelids swelled to the size of eggs, which frightened his comrades. The swelling increased, and was at its highest grade at the end of an hour, when the man came to his senses. There were some large and small black spots (ecchymoses) on his body, and his right eye was black, so that cornea and sclera were indistinguishable. He could feel quite well, and there were no nervous disturbances, oppression, or pain. For three days he was massaged, but the swelling persisted. Then, as a therapeutic measure, he was put into the diving dress, not without difficulty, and went down several times 16 to 17 metres, and stayed about ten minutes each time. On the fifth day he was much better. On the sixth day, after diving five times, his body had recovered its volume. The ecchymoses disappeared in fourteen days. In this case the sudden drop in pressure due to the bursting of the pipe produced a cupping effect and hæmorrhages. After the sudden decompression there resulted a general emphysema of the subcutaneous adipose tissue.

Aphasia seized a man who had already dived five times (20 to 22 metres, fifteen to sixteen minutes' duration, one minute decompression). On the sixth time he had to struggle at first against the movement of the boat, and spent ten minutes at 35 metres. Six minutes after decompression he had some headache, and looked as if he was thinking hard. He felt dizzy, and went to lie down, clenched his teeth, and lost consciousness. His stomach was swelled. His comrades rubbed this, and tickled his throat to make him vomit, a form of treatment they had much faith in. After two hours he came to, and laughed at seeing his comrades, who for a joke were tickling his penis with a feather. He could not speak a word, but understood all. After an hour he began to speak, and used the same word for everything, as "sponge" for "bread," etc. Speech soon returned, and after the night's rest he woke up well, landed, and went for a walk to "breathe the air." When he returned on board he was quite deaf, "could not even hear the clatter of the chain." He remained deaf three days, and on the fourth day dived. This improved the deafness, and after two days' more diving he recovered so that he could hear as well as before.

Another case suffered from sensory aphasia. He could hear the slightest sound and could speak, but could understand no spoken word. The only other symptom was a sensation of heat, which began in the feet and travelled up to the head. There was no paralysis. The sensory aphasia lasted under three hours.

Another was suddenly stricken blind, and the only words he could utter were, " Ha, ha, ha ! he, he !" He showed he could understand language by gestures. After five minutes the blindness vanished ; ten minutes later his legs became paralyzed ; twenty-four hours after speech returned. The paralysis lessened, but the cure was not complete ; the man limped, and there was stiffness and at times spasms of the limbs. After seven months he took to diving again, and stayed down till he sweated much (effect of CO_2 excess ?). This effected his cure. The " starting " of his limbs was always cured by diving once or twice.

Two men were seized with acute mania soon after their helmets were removed. One of these dived 44·8 metres, remained five minutes under water, and was " blown up " in four to five seconds. He was a " degenerate, liar, sodomist, and quarrelsome fellow." Five minutes after decompression he began to bluster, shout, grimace, bite, and tear his clothes. He was in constant movement, violent, and dangerous. Two or three were required to hold him. Ceaseless floods of talk came from him, ideas tumbling over each other on the hardness of his life, on his desires—these the most obscene, and obscenely expressed. He also saw wild beasts, and whimpered with fright, believed he was at the bottom of the sea finding "great, splendid sponges." *Over his heart very distinct gurgling sounds were audible.* The stomach was greatly dilated, and ructus and flatus frequent. After seven hours he recovered.

Among the English cases is the following—M. D., aged thirty-three, P.O., first class, was employed diving for a torpedo in 24½ fathoms of water at Lamlash. He was a man of exceptionally good physique, not obese, and perfectly healthy. A warrant officer was in charge of the diving party, and owing to the great depth of water, took particular notice of the time. He states the man took forty minutes to reach the bottom, that he remained there forty minutes, and took twenty minutes to come up. This latter he did himself slowly and steadily without hurry, the men in the boat only taking in the slack of the rope. He climbed up the ladder on the boat's side himself, and on the face-plate of the helmet being removed he said he felt all right, and then came into the boat with the ordinary assistance to be undressed. When the helmet was taken off, he answered a number of questions about his work, and gave a most detailed account of the same. He also joked with the other men, who all say they never saw him, or anyone else, come up in better condition. He felt perfectly well all the time he was in the water, suffered no inconvenience whatever, and only came up because it was so dark in the depth he was in that he could find nothing. He was cheerful and sensible, and had absolutely no symptoms whatever of anything wrong till some eight or nine minutes had elapsed from the time of his leaving the water. He then suddenly complained of pain in the stomach, and asked them to be quick and get off his dress, as he wished to get on board. In a second or two after he said, "Send for the doctor," and immediately slid down in the boat quite limp and unconscious. Fleet-Surgeon McKinley saw him at once, and found him in a comatose state. His skin was cyanosed, and his breathing was stertorous, laboured, and difficult. His lips were blowing and covered with froth. He was taken out of the dress and carried to the sick bay, but death took place before he got there—viz., about fifteen minutes after reaching the surface, and six to seven minutes from the first symptoms of illness. He had no vomiting, convulsions, or spasm of muscles at any time.

A post-mortem examination was made on the next forenoon, twenty-three hours after death.

Rigor mortis was well marked. Post-mortem staining marked about neck and lower limbs. On incising the scalp, a quantity of very dark-coloured, almost black, fluid blood flowed from the cut vessels, principally the temporals. On removing the calvarium, the veins over the whole surface of the brain were deeply engorged with the same dark fluid blood, and on removal of the brain a large quantity escaped from the vessels at the base. A careful examination was made of the pons, medulla, and upper inch of the cord. There was no evidence of any laceration or extravasation of blood. Numerous small bloodvessels were marked in the cord, etc., by the black puncta produced by the exuding black blood, but up to this no air was seen. On making sections of the hemispheres, nothing abnormal was noticed until the lateral ventricles were opened up. These contained little or no fluid. The striking point was the presence of bubbles of air in large quantities in the veins of Galen and choroid plexus. These had a beaded appearance, and showed prominently against the dark background of the plexus. On examination of the veins of the surface of the brain, which by this time were emptied of their blood, they were found to be in a similar condition. On opening the thorax, the lungs were found absolutely healthy. They appeared to contain less blood than usual, and were not engorged. The pericardium contained very little fluid. The heart was normal in size, but the veins on its surface under the serous membrane were markedly beaded with air. On lifting it up, it felt like a bladder half full of water, and, on making pressure to raise it, was heard to gurgle loudly, and a quantity of black, frothy blood flowed from the sinuses at the base of the skull. On opening the right ventricle, air came out with a puff, and a small quantity of black, frothy fluid blood was still found, but no trace whatever of any blood-clot. The left side of the heart was empty. All the valves were perfectly healthy.

On opening the abdomen, the small vessels of the mesentery at the attachment to the gut were found to be filled with air. The liver was very dark coloured and engorged, and on section the cut surface exuded such a large quantity of froth that it gave the impression that portions of the liver might float in water, but on trial they sank immediately. The spleen was black and enlarged, of a globular shape, 3½ inches in thickness. It was friable, and contained dark blood and air, the latter not to the same extent as the liver.

The cellular tissue in the subcutaneous fat of the abdomen and underneath the sternum also contained small bubbles of air.

The autopsy disclosed that all his organs were healthy and that the principal abnormal condition was the presence of air in large quantities in the right side of the heart and in the whole venous system.

The following extract from a short account by Fleet-Surgeon P. W. Basset-Smith, R.N.,* gives a vivid account of the dangers to which pearl divers in deep water are exposed :

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* *Lancet*, 1892, i., p. 309.

"While on board H.M.S. *Penguin*, employed in surveying a part of the north-west coast of Australia, which was then an important centre of the pearl-oyster fishery, cases of divers' paralysis came under my notice now and then. The luggers contain about six men, mostly Japanese, occasionally Europeans, and are accompanied by a schooner which acts as a store and hospital ship. All the work is done in diving dress in depths of from 10 to 25 fathoms, the period of submersion being often four or five hours. Cases of slight paralysis were common, coming on suddenly on removal of the dress, but generally recovering completely. The following is the worst case I saw:

"'Japanese, aged about thirty. Had been working in 32 fathoms (by all considered to be a dangerous depth) about three weeks ago; immediately on removal of the dress he became paralyzed, and has been so ever since. His condition was one of great emaciation, free from pain, but very apathetic. Temperature 103°; pulse 120; tongue furred; complete paraplegia with loss of control of bladder and rectum, and loss of sensation to the level of the umbilicus. There was a large deep bedsore over the sacrum, extending from the tuber ischii on either side to the crest of the ilium above, with a thick, black, extremely offensive slough partially detached. It had eaten through skin, fascia, and gluteus maximus, and in places exposed the bone.' (He died three days later.)

"The mate attending on him said that he had been as bad himself with bedsores and paralysis for eight months. He now walks with a limp, but muscular power is fair and tissues firm, knee-jerks increased. He said that a very bad sign is a localized swelling of the abdomen, from which, if allowed to get under the ribs, death is certain, and that they apply any pressure to keep it down, even sit on it (probably a paralysis of intestinal muscles and collection of flatus). Those in charge told me that they tried to prevent men from going down over 20 fathoms, but as they are paid by results, it is very little use."

Dr. Graham Blick (late District Medical Officer, Broome, Western Australia) has made the following interesting report:*

"From 1900 to 1908 I have had medical charge of probably the largest pearling centre in the world, including in its population upwards of 400 professional divers who are daily engaged

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* *Brit. Med. Journ.*, December 25, 1909.

gathering pearl-shell at depths varying from 7 to 20 fathoms. I have myself seen a diver bring up a shell from a depth of 25 fathoms (150 feet), but this was an exceptional feat. This means that these men are working under pressure, roughly, from 20 to 50 pounds per square inch above normal, the shifts varying in length inversely as the depth of working. In the lesser depth a diver will remain down one, two, or more hours, in the greater generally under half an hour. The ordinary rubber diving dress with metal helmet is the apparatus used, air being supplied by three barrelled pumps worked by hand-wheels. The divers are of various nationality—whites, Japanese, Filipinos, Malays, etc., the majority being Japanese, the whites being the least numerous. They work from small schooners of 10 to 14 tons, and range over many hundreds of miles off one of the most forlorn and desolate coasts in the world. Consequently, when an accident happens, they may be several days' sail from port, and so have not the advantages of their colleagues the 'caisson' workers, with their decompressing and recompressing chambers and immediate medical attention. Hence, many severe and often fatal cases of diver's paralysis occur.

"For eight years I have impressed on these men and their employers the fact that they can with very little extra time and trouble obtain all the safety conferred by the decompressing chamber by a slow and gradual return to the surface, and when this course has been followed, few, if any, cases of paralysis have occurred.

"Since 1900, not counting the slighter cases characterized by the men themselves as 'rheumatics,' I have had upwards of 200 cases of diver's palsy; 60 of the patients were dead before a doctor could be reached, and I made post-mortem examinations. Among the 140 odd who reached me alive I have had to deal with all degrees of paralysis, from slight paralysis of legs and inability to pass urine (always present) up to total paraplegia and loss of sensation. Clinically, the salient features of the paralysis are its bilateral distribution and the constant loss of the power of micturition. The legs are attacked before the arms, and recover later. Sensory nerves seem to suffer much less than motor, but I am bound to add that many cases had to be examined through an interpreter, and it is difficult in any case to get correct replies on such a matter from coolies. Out of these 140 cases 11 died, 8 from septicæmia consequent on sloughing and cystitis, and 3 from supervening meningitis. The rest, after a longer or shorter time, recovered, most of them completely, about 10 per cent. being permanently affected with slight paresis, generally of the anterior muscles of the legs.

"I have had patients who have been twice, thrice, or even oftener paralyzed, and who have more or less completely recovered. I have never seen extensive secondary degeneration of the cord follow, though one would expect this from the lesions found in the cord post mortem.

"The treatment after the establishment of paralysis is that of all organic nervous disease—one can only wait on Nature's efforts, though in this disease Nature is kinder than usual. General hygiene, massage, and electricity, all are useful to some extent, and, of course, any complications which arise must be treated. I have been often astonished at the way apparently hopeless paraplegics have recovered in the course of many months.

"The most troublesome cases were those complicated by cystitis and deep sloughing. The former complication is very frequently set up by imperfectly cleaned catheters used by the diver's friends, often for several days, while making for port. The paralysis of micturition is so well known among the men themselves that no diver would consider his outfit complete without a soft catheter. The sloughing is also the result in many cases of the treatment applied as first aid by the patient's friends, and is especially common among the Japanese, whose unbounded faith in very hot baths too often leads to parboiling and damage to the enervated tissues, forming the starting-point of frightful sloughing, which often defies all efforts of nursing to restrain. I have seen the sacrum, portions of the ilium, and the capsule of hip-joint absolutely denuded, and several of the deaths in my cases resulted from this condition. A few very bad cases, however, made wonderful recoveries. One case, a Filipino diver, was admitted to hospital with total paraplegia and sloughing over the buttocks, which extended till the right hip-joint, most of the sacrum, and the posterior portion of the crest of the ilium could plainly be seen ; yet after more than twelve months in hospital and several plastic operations he made a fair recovery, and was able to return to the Philippines.

"Owing to the distance from port at which these boats work, I have never been able to see a case in the earliest period of attack. The general history is that the diver has worked longer and deeper than usual, and then has hurried to the surface. He has felt quite well below, and gets aboard as usual. Often he has had the dress removed and even sat down to his meal before symptoms appear. Then he suddenly drops, sometimes 'as if shot'; or he may remark he is not feeling well, and the symptoms come on more gradually. He may or may not lose consciousness. Some rapidly fatal cases have occurred without initial loss of consciousness, and it is practically never lost in slight attacks. Death may occur within an hour, or not until after a day or two.

"Clinical experience directs attention to the spinal cord in this disease, and my sixty autopsies have amply corroborated the inference that here is to be found the greatest mischief. I have never found the classical 'bubble of nitrogen' in the hearts of my cases; indeed, I honestly confess I doubt my ability to recognize a bubble of nitrogen. I have, however, often fancied that during the rapid putrefaction of these bodies there has been a larger evolvement of gases and greater distension of the tissues than is the case with other bodies after equally sudden death. Almost invariably the heart, lungs, and large veins are engorged with dark liquid blood.

"In my experience the following appearances are typical of diver's paralysis on post-mortem examination of a rapidly fatal case. The thoracic viscera and large veins of the neck are engorged with dark liquid blood. There is nothing noteworthy in the abdomen. There is more or less venous engorgement in the meninges of the brain, markedly increasing towards the base, especially round the medulla. Section of the brain is generally negative; sometimes the blood-points seem rather larger than usual. I have only once found a hæmorrhage in the brain; it was about the size of a horse-bean, and situated in the left internal capsule, and was accompanied by another hæmorrhage practically severing the spinal cord opposite the body of the fifth cervical vertebra. The most characteristic signs are found on exposing the spinal cord. The dural cavity contains blood or blood-stained fluid, the meninges of the cord are congested with blood, and the congestion appears to be most intense in the cervical region, say the portion corresponding to bodies of the fourth to the sixth cervical vertebræ. This portion of the cord appears to me to be the diver's calx Achillis. It is here that the characteristic 'teasing' is most apparent. I call it teasing for want of a better word to explain the appearance in the section of cord; it looks as if one had stippled the face of the section with a fine knife or needle, a semi-disintegrated appearance. With this condition is nearly always associated hæmorrhage of greater or less extent, also most marked in the above portion of the cord; indeed, I have never found an effusion of any size except in this part. Here they may range in size from mere points of blood to, as I have seen in nine cases, large hæmorrhages practically cutting the cord in two, and forming clots filling the meningeal tube for over 1½ inches. I had neither time nor appliances for microscopical pathology."

Dr. Blick made his post-mortem examinations too long after the onset of illness to find evidence of air bubbles. He says:

"When I first met with this disease I was greatly handicapped by the want of literature on the subject. Consequently I was presented with a pathological problem which I had to unravel as best I could, and was often sorely puzzled. For instance, I noticed that though the divers started work about March, there were practically no cases of paralysis before September, and from thence to the end of the working season, about the end of November, cases came in almost daily. All sorts of theories are current among the men themselves accounting for this well-known fact—for example, working farther out in deeper water, that the water itself 'gets heavier' at this end of the season, etc.

"The mystery was elucidated by the discovery in one autopsy of signs of scurvy. There was the simple explanation of the prevalence of the disease among men who live for months on small boats, eating salted and tinned foods, and also of its infrequent occurrence till the bloodvessels have been somewhat weakened, as we know happens in scurvy. Acting on this knowledge I preached an anti-scurvy crusade, and noted that in fleets where my advice was taken and extra vegetables and other antiscorbutic precautions used there was a very considerable reduction in the number of cases of paralysis."

The scorbutic condition would, by enfeebling the circulation, lengthen the time of desaturation, and increase the number of attacks.

CHAPTER V

THE NATURE OF CAISSON SICKNESS—*Continued*

The caisson works at Nüssdorf, on the Danube, gave origin to the valuable work of Heller, Mager, and von Schrötter,* who, making an exact study of the illness, tabulated the cases thus :

	Number of Cases.	Percentage.
Ear trouble, pain, hæmorrhage, etc.	68	21·5
Myalgia	105	32·8
Arthralgia	60	18·8
Phenomena in the trunk of the body, girdle pain, chest pressure, etc.	10	3·1
Monoplegia	17	5·3
Paraplegia	26	8·1
Ménière's symptom complex	14	4·4
Apoplectiform deafness	2	0·6
Vertigo	4	1·3
Aphasia	1	0·3
Asphyxia	13	4·0

They state that "bends" showed no predilection for that part of the body which had been most used in the work. The symptoms generally came on half an hour, at most six hours, after decompression. The higher the pressure, the greater the number of cases ; there were none below 2·4 atmospheres absolute. This is the critical pressure. Workmen used to compressed air suffered as much as green hands. Nature of the soil, operation of concreting, etc., had no influence.

The cases of ear trouble were of two kinds: (1) Cases of temporary deafness and vertigo, lasting not more than eight to fourteen days, and caused by non-equalization of the pressure on either side of the drum during compression. The tympanic membrane showed signs of congestion, and there appeared in

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* *Luftdruck Erkrankungen*, Wien, 1900.

some cases hæmorrhages either in its substance or in the middle ear. Blood-stained sputum might be coughed up from the back of the throat, the blood coming from the Eustachian tube. (2) Cases of Ménière's "complex," vertigo, vomiting, and deafness—symptoms which might persist indefinitely, and were caused by lesions produced by air bubbles, either in the central tracts of the cochlea, or vestibular nerve, or in the internal labyrinth of the ear. The pains in the myalgias and arthralgias were of tearing, boring, gnawing, or lancing character, and were made worse by active or passive movements. Swelling of the joints or muscles sometimes resulted.

The paralysis of the legs, when it occurred, might last a few minutes, hours, or even eighteen days, and then disappear, or persist. It was of a spastic character. The patients while recovering took short steps insecurely with the legs held stiffly, and were unable to stand or walk with the eyes shut. There occurred sometimes spasmodic movements of the adductor groups of muscles. The reflexes were exaggerated, and even strong tremors or convulsive movements might be elicited; the excitability to the faradic or galvanic current was usually increased. There seldom followed atrophy of the muscles and loss of reflexes. The increased reflexes persisted after recovery from the paralysis.

Paralysis of the bladder, with incontinence, usually accompanied the paralysis of the legs, and with this there might be genital impotence, priapism, and ejaculatio præcox, paralysis of the bowel, and incontinence of fæces. Decubitus occurred in the worse cases of paralysis, and huge sloughing bedsores and infection of the bladder and kidneys terminated the life of these cases.

On the side of sensibility "puces," or formication, and painful itching were most common symptoms. The writer has no doubt that these are produced by air bubbles in the fat of the subcutaneous tissues. The lividity and marbling of the skin is to be attributed to air embolism of cutaneous vessels, and in the cases of paralysis there might be girdle sensations, and pain and temperature sense might be lost, and touch retained in the legs, or *vice versa*.

Monoplegias have been observed, and sometimes, as in Erb's disease, the paralysis affects the muscle groups engaged in the performance of some particular function. The cerebral nerves were rarely affected, but cases of disturbance of the functions of the second, seventh, fifth, and oculo-motor nerves have been recorded. The brain escaped generally, in comparison with the spinal cord, because of its far ampler supply of blood. Psychical alterations have resulted in some cases, such as exaltation and forced movements, hallucination, incoherence, and amnesia.

There were two cases of asphyxia and death at Nüssdorf:

Case 1.—The man (aged thirty-one) worked a four-hour shift at +2·2 atmospheres, and was decompressed in eighteen minutes. Half an hour later he was taken with increasingly severe tearing pains in the hands and feet; air hunger ensued, his face became blue, his lungs rattled, and he died about two hours after leaving the caisson, before a doctor came. He had told a comrade that he had felt bad, and had eaten nothing that day.

Post-mortem examination thirty-two hours after death showed small gas bubbles in the vessels of the pia mater; the lungs were full of a foamy blood-stained serous exudation. There was foamy blood in the liver. No gas was found in the heart. The acute pulmonary œdema resulted from gaseous embolism of the pulmonary arteries, and suffocated the man.

Case 2.—The man had worked 536 shifts without harm. After a shift of four hours at +2·3 atmospheres, he was decompressed, so far as could be ascertained, in over thirty minutes. A short time after he was taken with violent pains in and below the knee-joints. He was recompressed to +2 atmospheres, and after an hour was decompressed in forty minutes. The pains had almost gone. They came back again after three-quarters of an hour. Next day the man was well again, and worked two shifts of four hours. A short time after decompression he was again seized with pain in the left knee, so severe that he groaned and moaned. The knee was rubbed and warmed, and became easier. He had some oppression on the chest, but no cyanosis or dyspnœa. After waiting an hour, he left the works with a comrade, in spite of advice to remain under the doctor's care, and did not return till three hours later, after, it is said, drinking several glasses of wine in an inn. He was seen breathing heavily, with his arms on the bed and kneeling in front of it. He was given some coffee and helped into bed, and was found dead there when the attendant went to call him three hours later. Death took place in this case five hours after a period of freedom from trouble. At the autopsy gas was found in the right heart. There was nothing to be seen in the left knee.

Two other cases are of especial interest. The first was one of *asphyxia and apoplectiform deafness.* The worker, after a shift of four hours at + 2·2 atmospheres, was taken with severe pains in the chest and limbs, a girdle sensation, and difficulty in breathing. There was ptosis on the right side, and nystagmus on both sides. Cold sweat and cyanotic coloration of the face and chest; irregular heart action. The dyspnœa and cyanosis increased, and marbling of the skin with dark red flecks appeared. The man said he was too weak to breathe, but must drink. Vomiting interrupted his drinking. Rattling sounds were audible in the lungs. His feet became cold, the pulse too weak to feel. He was given stimulants, friction to the feet, and bled 300 grammes; no foam or bubbles in the blood. After this he improved, but complained of hearing badly, and vertigo. There were painful swellings about the right shoulder and elbow, and of both knee-joints. Noises in the ears, deafness, vertigo, vomiting, and pains in the head persisted, and the man ultimately became insane.

The second case was one of *asphyxia and paraplegia.* The man suddenly collapsed two hours after a shift at + 1·7 atmospheres, when setting about to write a letter at home. He was seized with clonic and tonic spasms, producing intense opisthotonos and dyspnœa; was cyanotic and unconscious, with a pulse scarcely to be felt. Rattling noises were heard in the lungs, and ecchymoses seen in the skin. He was recompressed and given artificial respiration, as the pulse and natural breathing almost failed. When the pressure reached + 1·5 atmospheres, he began to recover consciousness. Paraplegia ensued, and recovery was incomplete.

In New York four great tunnel systems have been built under the East and North Rivers by means of compressed air.

The East River tunnels were contracted for by S. Pearson and Sons, and between March, 1906, and July, 1908, four tunnels of a diameter of 23 feet each were driven under the East River from the foot of East Thirty-Third Street on the Manhattan side to East Avenue on the Long Island side, a distance of 6,176 feet. The building of these tunnels is the greatest undertaking carried out by compressed air. The pressure used during the two years averaged + 32 pounds; at times + 42 pounds was necessary. More than 10,000 men were medically examined and passed for the work, and when the work was in active progress about 1,000 men a day were kept at work in the headings. The medical staff was made up of six physicians, with one always on duty, and four hospital orderlies.

The most valuable report of recent years has been made by Dr. F. L. Keays* on the 3,692 cases which occurred among the 10,000 men (= 36·92 per cent.). There were 20 deaths (= 0·2 per cent.). On the basis of man-shifts (557,000) the percentage of illness was 0·66 ; of death, 0·0035. Keays divides the cases into—

A. Cases showing pain in various parts of the body (" bends "), 3,278, or 88·78 per cent.

B. Cases with pain, also having local manifestations, 9, or 0·26 per cent.

C. Cases showing pain, together with prostration, 47, or 1·26 per cent.

D. Cases showing symptoms referable to the central nervous system—

1. Brain (hemiplegia), 4, or ·11 per cent.
2. Spinal cord—

(*a*) Sensory disturbances ..	36
(*b*) Motor disturbances ..	34
(*c*) Sensory and motor disturbances	10
	80, or 2·16 per cent.

E. Cases showing vertigo (" staggers "), 197, or 5·33 per cent.

F. Cases showing dyspnœa and sense of constriction of the chest (" chokes "), 60, or 1·62 per cent.

G. Cases showing partial or complete unconsciousness, with collapse, 17, or 0·46 per cent.

Fatal cases—

Group C	6
,, D	5
,, G	9
	20, or 0·54 per cent.

* " Compressed Air Illness," New York, 1909.

Localized pain, vertigo, and dyspnœa seldom, if ever, prove fatal. Death may result from affections of the vital centres of the brain, or may follow the complications of lesion in the cord, such as cystitis, pyelitis or pyonephritis, ascending myelitis with diaphragmatic involvement and pneumonia, bedsores, etc., or permanent paraplegia may result. Cases of pain with prostration generally recover, but some die. Cases of unconsciousness and collapse are often fatal.

Granted that the presence of free gas in the blood or tissue fluids is the cause, it is evident that the variety and severity of the symptoms will depend upon—(1) The volume of gas set free, and (2) the place where it is lodged. If the arteries supplying vital centres of the brain or the pulmonary arteries are embolized, death may result. Such is the cause of the cases of unconsciousness and collapse. Dyspnœa and chest oppression results from partial air embolism of the pulmonary arteries. Air bubbles formed in unyielding tissues, such as ligaments, fasciæ, periosteum, and the Haversian canals of bone, muscle spindles, nerve sheaths, will cause "bends" of greater or less severity. Air embolism of the arteries of the spinal cord, and bubbles formed in the white matter itself, are the cause of the paraplegia so commonly observed; while monoplegia, hemiplegia, and aphasia result from embolism of cerebral vessels, likewise sensory paralytic symptoms, such as blindness, sensory aphasia; vertigo, Ménière's symptom complex from air bubbles in the labyrinth. No symptoms at all may result from air bubbles in the liver, spleen, kidneys, adipose tissue, or veins. With increasing amounts of free gas in the blood and tissues, the symptoms become more general, pain may be suffered in various parts, and prostration or collapse may result.

Cases of Pain in Various Parts.

Fleeting pains are probably felt in some part of the body shortly after decompression by most caisson workers who endure anything like +2 atmospheres pressure. The legs are most frequently the seat of the pain—*e.g.*, pain in one leg, 1,277 cases; in one arm, 568 cases. The pain is generally about the knee-joints. In the arms the pains occur most frequently about the elbows or shoulders. The pain may be slight and transient, or severe, and last several days. Exercise, massage, or counter-irritation will give relief to the mild cases; but often these means fail, and the pain may increase in severity and spread to other parts. It may be localized, or radiate, following the course of the nerve, and may be deep-seated and boring, as if in a bone, or dull or cutting in character. If severe, pallor and sweating accompany it. In a few cases there are local symptoms, such as subcutaneous emphysema and swelling. In two such cases Erdman was able to demonstrate the presence of gas bubbles by means of an aspirating syringe partly filled with alcohol. The patient's leg and operator's hand were both submerged under water, and the swelling punctured. When the piston was drawn, bubbles of gas streamed up through the alcohol. In four cases there was developed brawny œdema of the part, suggesting lymphatic obstruction; in five other cases the swelling was "evidently due to accumulations of free gas beneath a fascia, or within a bursa, or tendon sheath." "A slight emphysematous crackle could be felt" on deep palpation of a swelling above the knee.

It is proved that these cases are due to local and not central causes by these local manifestations, and by the fact that there are no signs of cord irritation, such as augmented reflexes, motor or sensory disturbances, loss of control over bladder and rectum. The pains shift, too, from one place to another.

The larger proportion of cases of "bends" is explained by the slow desaturation of such parts as fasciæ, tendon sheaths, bursæ, nerve sheaths, sensory end bulbs, etc. "The chances that gas emboli will involve an extremity or other parts of the body, such as unimportant organs or tissues, are far greater than that they will attack a vital centre or central nervous area."

CASES OF PAIN AND PROSTRATION.

The pain is usually more or less general, and may affect the abdomen. The patient is pale, sweats, and complains of feeling weak and dizzy; he may vomit. The pulse is 120 or more, small, irregular, and of low tension. Mottling of the body was noted in thirteen cases, varying from an erythematous blotching to a hæmorrhagic eruption, and from small spots to areas as large as the hand. This kind of case may pass over into coma and collapse, and the symptoms signify a considerable amount of free gas in the bloodvessels.

CASES SHOWING SYMPTOMS REFERABLE TO THE CENTRAL NERVOUS SYSTEM.

CASES IN WHICH THE SYMPTOMS POINTED TO EMBOLISM OF CEREBRAL VESSELS.—1. Partial loss of power in left arm and leg, relieved by recompression.

2. Almost complete paralysis of right leg, and partial paralysis of right arm. Reflexes plus on this side. Cured by recompression.

3. Loss of power in left arm and leg. Reflexes plus. Cured by recompression.

4. After working eight hours in +15 pounds pressure, decompressed in two to three minutes. Soon after lost power over right arm and leg, and could not speak. Cured by recompression.

SPINAL CORD CASES.—Thirty-six showed sensory disturbances, nine had numbness or pricking sensations in one leg (one of these later had pain in both legs); twenty-seven had pricking or numbness in both legs, and seventeen of these also had abdominal pain, and one difficulty in voiding urine. It is probable that some of these cases were due to peripheral nerve irritation. Thirty-four showed motor disturbances.

1. Pain in legs and abdomen, partial loss of power in left leg. Pain only relieved by recompression. Recovered in two weeks' time.

2. Eleven cases had partial loss of power over both legs (three had abdominal pain also). All cured by recompression.

3. Partial paralysis of one leg, and complete paralysis of other leg. Cured by recompression.

4. Pain in abdomen and limbs, partial paralysis of both legs, prostration, blotching of chest and abdomen. Recompressed four times in twenty-four hours with improvement each time. Recovered third day.

5. Partial loss of power both legs; retention of urine. Returned to work in two weeks.

6. Partial loss of power both legs; retention of urine. Recovered in one week.

7. Partial loss of power of both legs; retention of urine. Sent to hospital. Result not reported.

8. Partial loss of power both legs; retention of urine. Relieved by recompression. A few hours later partial paralysis returned.

Returned to work in one week. Two years later examination showed that he walked unsteadily and with a spastic gait. Romberg sign present, and knee-jerks exaggerated. Said he had to use catheter.

9. Seven cases of complete loss of power over both legs. All cleared up on recompression.

10. Complete paraplegia, retention of urine, no improvement on recompression. Finally, regained use of leg, so that he could walk with difficulty.

11. Pain in both legs, recompressed twice with slight relief. After second time loss of power over legs and retention of urine. Improved in hospital.

12. A "green-hand" preliminary test one hour at 33 pounds, decompressed in sixteen minutes. Paraplegia fifteen minutes later. Improved under recompression, and could walk. After paralysis returned with loss of control over bladder and rectum. Eighteen months later could walk with spastic gait.

13. Partial paralysis of both legs, loss of control of bladder and rectum. In hospital two weeks. Died few weeks later. Cause of death unknown.

14. Five cases of paraplegia, no improvement from recompression. All resulted in death.

Sensory and Motor Disturbance.—1. Three cases of numbness and partial loss of power in both legs. Cured by recompression.

2. One case of numbness and partial loss of power in both legs. Symptoms returned next day in one leg. Unrelieved by further recompression.

3. (*a*) Numbness and loss of power in one leg. (*b*) Complete loss of sensation and power in one leg; cured by recompression.

4. Complete loss of power in one leg; relieved by recompression. Later complained of dead feeling in both legs and abdominal pain; cured by second recompression.

5. Two cases complete loss of sensation and power in both legs; cured by recompression.

CASES SHOWING VERTIGO.

One hundred and thirteen had vertigo only; 42 had vertigo and vomiting; 29 vertigo and pain in limbs; 4 vertigo and abdominal pain; 6 vertigo and dyspnœa; 1 vertigo, pain in the chest, and numbness in one leg; 2 vertigo, prostration, and mottling.

Snell first called particular attention to this class of case in connection with the Blackwall Tunnel caissons, and ascribed the cause to air bubbles in the labyrinth or labyrinthine hæmorrhage. Von Schrötter has caused hæmorrhages in the labyrinth of animals both by rapid compression and decompression. In the case of a dog, which exhibited Ménière's symptom complex after decompression, there was no lesion of the ear found, nor in another dog with similar symptoms after artificial production of air embolism.

Vertigo may be produced by contradiction of or confusion between sensory impressions, and air bubbles in the brain may cause this.

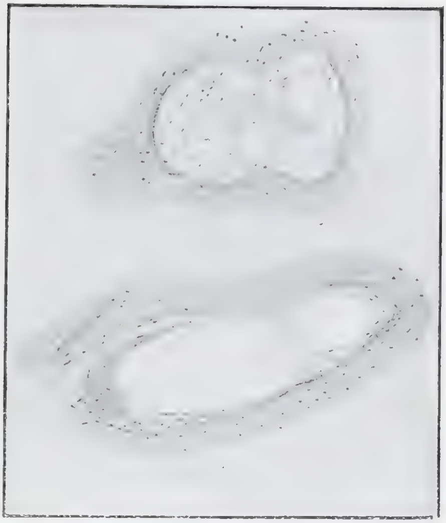
Fig. 36.—Hæmorrhage in the Semicircular Canals of Guinea-Pig (von Schrötter).

Cases showing Dyspnœa and Sense of Constriction of Chest ("Chokes").

Alarming in appearance, this condition readily yielded to recompression. "Many, but not all, of our cases occurred when blasting was going on in the tunnel." It resembles asthma both in appearance and physical signs. The cause probably is a certain amount of air emboli in the pulmonary vessels, with consequent œdema of the air-tubes.

Cases showing Partial or Complete Unconsciousness and Collapse.

1. Semi-conscious; marked prostration. Improved by recompression except for pain in knee.
2. Semi-conscious, prostration; cured by recompression. Complained of abdominal pain when in medical lock.
3. Unconscious and moribund. Mottling of body. Regained consciousness under recompression; general condition improved, but still very weak. Recovered four days later.

4. While drinking in neighbouring saloon suddenly became unconscious. Regained senses under recompression, and complained of extreme weakness. Improved by second recompression. Recovered two days later, except for some weakness in right arm.

5. Brought to medical lock unconscious, breathing stertorous, skin bathed in perspiration. Recovered senses on recompression. Condition good afterwards; went home quite well, after resting six hours.

6. Semi-conscious, marked prostration, mottling on abdomen. Became conscious and could walk on recompression, but complained of pain in all extremities. Recovered at end of recompression.

7. Semi-conscious, marked prostration, dyspnœa, gastric disturbance, mottling of trunk. Developed systolic murmur at heart apex. Improved by two recompressions, but still weak. Went home after twenty-four hours. Later had sharp pain in left side of chest and hæmoptysis lasting several days. Was well at the end of two weeks.

8. Man aged twenty-six had worked several months in compressed air. After working from 7 to 10 a.m., and 1 to 4 p.m., under +34 pounds, went home. At 4.45 p.m. began to have general pain and weakness. When Dr. Keays arrived the man was crying out with pain, pale, cyanosed, and sweating; pulse frequent and weak. Before the ambulance arrived the patient became unconscious, respirations stertorous, radial pulse almost imperceptible. When moved from the bed to the stretcher he stopped breathing for what seemed a minute or more. The pulse disappeared, and he seemed to be dying. Strychnine sulphate, $\frac{1}{3}$ grain, injected. Respirations began again. Transferred rapidly to medical lock and recompression begun at 5.15 p.m. Massage given. For some time there was no improvement, but at about 6 p.m. the colour was better, and the pulse could be felt. At 6.30 he regained consciousness and could answer questions. Colour fair; pulse 60, irregular; respiration 28. He could sit up, but felt very weak. Continued to improve during very slow decompression. Mottling was marked at one time, but became fainter. Decompression completed at 11 p.m. Wholly conscious; can sit up with difficulty; colour good; no sweating; pulse still weak, 120 per minute; heart and lungs normal; abdomen very tender, but not

rigid nor distended; mottling faint; temperature 98½° F. No paralysis. Discharged from hospital cured four days later.

Abdominal pain, says Dr. Keays, is a symptom which is justly feared by workers in compressed air. It often occurs with lesions of the spinal cord, and is analogous then to girdle pain. In many of the severest cases it was a symptom. "With simple abdominal pain one can never feel sure that a serious case is not threatened." In cases other than spinal it probably signifies—air in the abdominal vessels—dangerous, if much in amount, for productive of pulmonary embolism.

Mottling of the skin is also a sign of gravity, for it signifies free gas in the subcutaneous vessels and fat. Itching of the skin, "puces" of the French caisson, is a common symptom, but did not come much under the notice of Keays, probably owing to its trivial nature.

REPORT OF TWENTY FATAL CASES AT EAST RIVER'S TUNNEL

(F. L. Keays).

1. English. Age 30. New worker. Pressure, + 34 pounds. Time under pressure (T.u.P.), 3 hours. Time of decompression (T.o.D.) (?).

Symptoms (15 minutes after decompression).—Abdominal pain, followed soon by unconsciousness and collapse.

Treatment.—Recompressed twice. Slight improvement under pressure. Died 7 hours after attack.

Autopsy Findings.—Coroner's case. Dr. Gould present, gave report. Free gas bubbles in right heart and in inferior vena cava. Organs negative.

2. German. Age 28. Old worker. P., + 34 pounds. T.u.P., two 3-hour shifts. T.o.D., a few minutes.

Symptoms (15 minutes after decompression).—Dizziness, weakness in legs, followed soon by total paralysis of legs and partial coma. Later, paralysis of arms.

Treatment.—Recompressed twice. No improvement.

Died about 24 hours after attack.

Autopsy Findings.—Coroner's case. New York Hospital Reports. Beard poorly developed, axillary hair slight, pubic hair abundant. Face effeminate. Right inguinal glands enlarged and firm. Heart normal, except that myocardium is greyish-red in colour, and presents a peculiar mottled appearance. Heart muscles flabby and moderately friable. Aorta of small calibre throughout, walls of aorta and of abdominal branches very thin and elastic. Lungs, moderate emphysema. Both lungs congested; marked œdema of right, slight of left. Pleuritic adhesions over left lower lobe. Thymus persistent, weighs 30 grammes, normal on sections. Tracheal glands enlarged. Lingual, faucial, and pharyngeal tonsils enlarged. Spleen enlarged. Kidneys normal. Gastro-intestinal tract normal, except for hyperplasia of Peyer's patches near ileo-cæcal junction, and enlarged mesenteric glands. Liver negative. Brain macroscopically negative. Venous sinuses, no gas bubbles, excepting in veins leading up from cord. Spinal cord, pial vessels injected. No macroscopic lesions in cut sections of cervical, dorsal, and lumbar regions. No record of microscopic examination of cord.

3. Finn. Age 18. New worker. P., + 34 pounds. T.u.P., 3 hours. T.o.D., ?

Symptoms (15 minutes after decompression).—Sudden unconsciousness and collapse.

Treatment.—Recompressed once. No improvement.

Died 2 hours 15 minutes after attack.

Autopsy Findings —Coroner's case. Was unable to get report of autopsy.

4. Hungarian. Age 35. Worked half a shift day before. P., + 33 pounds. T.u.P., two 3-hour shifts. T.o.D. (?)

Symptoms (30 minutes after decompression).—General pains, weakness. Coma after 36 hours, lasting until death.

Treatment.—Recompressed once. Slight improvement.

Died 8 days after attack.

Autopsy Findings.—Coroner's case. Dr. Keays present. The subject showed the gross lesions of broncho-pneumonia, chronic nephritis, endopericarditis, and congestion of the liver.

5. Coloured. Age 31. Old worker. P., + 33 pounds. T.u.P., 3 hours. T.o.D., (?)

Symptoms (2 hours after decompression).—Weakness, vomiting, sense of constriction of chest. Later collapse, but conscious. Signs of œdema of lungs.

Treatment.—Recompressed once. Slight improvement under pressure.

Died 3 hours 45 minutes after attack.

Autopsy Findings.—Coroner's case. Dr. Erdman present, gave report. No organic lesions found. Much gas under pressure in vena cava inferior. Lungs œdematous, but with air in parenchyma. Gas bubbles in visceral veins.

6. Hungarian. Age 19. Old worker. P., + 33 pounds. T.u.P., 3 hours. T.o.D., 18 minutes.

Symptoms (30 minutes after decompression).—Abdominal pain, weakness in legs, partial coma. Later total paralysis of legs.

Treatment.—Recompressed once. No improvement.

Died 18 days after attack.

Autopsy Findings.—No autopsy. Diagnosis, New York Hospital Reports: Caisson disease, transverse myelitis. Complications: cystitis and pyelitis, pernicious vomiting.

7. Austrian. Age 32. New worker. P., + 33 pounds. T.u.P., 3¾ hours. T.o.D., 15 minutes.

Symptoms (15 minutes after decompression).—Sudden unconsciousness and collapse.

Treatment.—Artificial respiration and stimulation.

Died 20 minutes after attack.

Autopsy Findings.—No autopsy.

8. Hungarian. Age 35. Claimed to have worked two weeks at 32 pounds pressure. P., + 33 pounds. T.u.P., 3 hours. T.o.D., 19 minutes.

Symptoms (30 minutes after decompression).—General pains and weakness. Later coma and collapse. Mottling of body.

Treatment.—Recompressed twice. No improvement.

Died 5 hours after attack.

Autopsy Findings.—Coroner's case. Dr. Erdman present, gave report. Blood everywhere charged with gas bubbles. Gas under pressure distending right heart. Heart normal. Aorta slightly narrower than normal. Lungs small, encysted old tuberculous focus in left upper lobe. A dilated bronchus in right lower lobe (not thought to be significant). Lungs free from gas bubbles. Spleen, hyperplasia of lymphoid tissue. Liver shows syphilitic lesions. Kidneys normal. Thymus persistent; weighs 27 grammes. Brain and spinal cord macroscopically negative.

9. **Coloured.** Age 38. Old worker. P. + 33 pounds. T.u.P., 3 hours. T.o.D., 17 minutes.
Symptoms (30 minutes after decompression).—Dizziness, followed soon by unconsciousness and collapse. Convulsions and right hemiplegia just before death.
Treatment.—Recompressed twice. Some improvement on first recompression.
Died 12½ hours after attack.
Autopsy findings.—Coroner's case. New York Hospital Records. Heart negative, except for patulous foramen ovale. Lungs, moderate œdema and congestion. Spleen, kidneys, and liver normal. No gas in veins nor in heart. Brain, moderate œdema.

10. **Armenian.** Age 19. Old worker. P., + 30 pounds. T.u.P., 3 hours. T.o.D., 8 minutes.
Symptoms (30 minutes after decompression).—Pain in abdomen and loss of power and sensation in both legs. Paralysis did not improve. Had to be catheterized. Developed cystitis, bedsores, pneumonia, tuberculosis.
Treatment.—Recompressed twice. No improvement.
Died 144 days after attack.
Autopsy Findings.—Coroner's case. New York Hospital Records: Lungs, adhesive pleurisy both sides. Tuberculous processes both lungs, patches of pneumonia left lung. Brain, leptomeninges œdematous. Anterior frontal convolutions show a slight grade of atrophy. Brain substance very soft and œdematous. Ventricles distended with clear serous fluid. Cord, dura normal. Entire lowermost portion of dura fluctuates. Spinal fluid considerable in amount. Cervical portion of cord appears normal. Dorsal and lumbar portions unusually small, extremely soft, almost diffluent; on section, moist, translucent; the greater part of white matter appears to be involved; changes not confined to any particular column.

11. (Never examined; went to work on another man's badge). P., + 32 pounds. T.u.P., 3 hours. T.o.D., 19 minutes.
Symptoms (30 minutes after decompression).—Sudden unconsciousness and collapse.
Treatment.—Died while being recompressed.
Died 15 minutes after attack.
Autopsy Findings.—Coroner's case. Dr. Erdman present, gave report. Subcutaneous emphysema over shoulders and anterior aspect of thighs. Right ventricle of heart and bloodvessels everywhere surcharged with free gas. Heart, lungs, liver, spleen, and kidneys, all normal, except for congestion. Small ecchymoses beneath the scalp. The meningeal veins full of gas emboli.

12. **American.** Age 27. New worker. P., + 28 pounds. T.u.P., 4 hours. T.o.D., 5 minutes for second lock; total, 10 minutes.
Symptoms (about 10 minutes after decompression).—General pain and weakness, followed soon by unconsciousness and collapse. Mottling of entire body.
Treatment.—Recompressed once. Remained unconscious under pressure.
Died 19 hours after attack.
Autopsy Findings.—Coroner's case. Report at inquest. Heart normal. Lungs, chronic adhesive pleurisy, right side. Mild grade of chronic nephritis. Slight localized œdema, right side of brain. Some free gas emboli in veins scattered throughout body.

13. **Italian.** Age 31. New worker. P., + 30 pounds. T.u.P., 8 hours, T.o.D., 5 minutes for second lock; total, 10 minutes.
Symptoms (about 1 hour after decompression).—General pains, with weakness. Intense mottling of arms, thighs, chest, and back. Three days later developed paralysis of both legs.

Treatment.—Recompressed three times, with slight improvement.

Died 4 days after attack.

Autopsy Findings.—Coroner's case. New York Hospital Records: Hæmorrhagic areas, large and small, on thorax, abdomen, and extremities. Left pleura shows old adhesions at lower margin externally. Heart auricular chambers distended, with dark fluid blood; right and left sides show post-mortem clots. Anterior groups of papillary muscles are replaced by fibrous connective tissue. Mitral valves show firm, rounded, smooth margins. Muscle fibres are distinctly paler in endocardial half. In posterior portion of interventricular septum at base is an area of fibrous replacement, measuring 2 + 2 centimetres. Coronary arteries normal. Lungs, œdematous on section. Spleen and pancreas normal. Liver intensely congested. Gastro-intestinal tract, hæmorrhages into mucosa of jejunum and ileum, marked in latter. Kidneys and adrenals negative. Ecchymoses in pleura of posterior mediastinum about thoracic aorta. Bladder mucosa shows few ecchymoses at base. Brain negative. Cord, few small hæmorrhages into grey matter at different levels.

14. COLOURED. Age 28. Old worker. P., + 30 pounds. T.u.P., 7½ hours. T.o.D., 1 minute for second lock; total, 5 minutes.

Symptoms (directly after decompression).—Pain in lumbar region and weakness in both legs, followed by complete loss of power and sensation. Had to be catheterized until death. No improvement in paralysis.

Treatment.—Recompressed twice. No improvement.

Died 91 days after attack.

Autopsy Findings.—No autopsy. Diagnosis, New York Hospital Records: Caisson disease, transverse myelitis. Complications: asthenia, infected bedsores, cystitis.

15. HUNGARIAN (?). Age 37. New worker. P., + 30 pounds. T.o.P., 8 hours. T.o.D., 17 minutes.

Symptoms (30 minutes after decompression).—Dizziness and general pains, with marked weakness.

Treatment.—Recompressed three times. No improvement.

Died 14 hours after attack.

Autopsy Findings.—Coroner's case. Dr. Erdman and Dr. McWhorter present, gave report. Brain and cord not examined. Gas bubbles largely distributed throughout venous system. Thymus gland appears to be abnormally enlarged. The viscera, so far as examined, were normal.

16. ITALIAN. Age 30. Old worker. P., + 30 pounds. T.u.P., 8 hours. T.o.D., 15 minutes.

Symptoms.—Found dead in the street about one hour after decompression.

Died about 1 hour after attack.

Autopsy Findings.—Coroner's case. Dr. Erdman and Dr. McWhorter present, gave report. Moderate mottling of body. Subcutaneous emphysema of lower abdomen and along the large veins of arms and legs. Thorax and abdomen opened, showing veins well occupied by free gas. Right heart distended by gas. Lungs normal. Kidneys normal, except for congestion. Liver normal. (On section, bubbles of gas exude from veins.) Brain and cord not examined.

17. ENGLISH. Age 39. Claimed to have been a diver. New to our work. P., + 33 pounds. T.u.P., two 3-hour shifts. T.o.D., 15 minutes.

Symptoms (30 minutes after decompression).—General pain, marked weakness. Mottling of body.

Treatment.—Recompressed several times during 48 hours, with improvement while under pressure.

Died 50 hours after attack.

Autopsy Findings.—Coroner's case. Dr. McWhorter present, gave report. A few small gas bubbles in the small mesenteric veins. No gas in right heart nor in any of the larger vessels. Heart normal. Liver somewhat small. Other viscera not examined.

18. Coloured. Age 29. Old worker. P., + 32 pounds. T.u.P., 8 hours. T.o.D., 20 minutes.
Symptoms (15 minutes after decompression).—General pains, followed soon by complete paralysis of both legs. Later ascending paralysis; arms and chest muscles involved. Had to be catheterized. Hæmaturia.
Treatment.—Recompressed twice; with improvement first time, none second.
Died 10 days after attack.
Autopsy Findings.—No autopsy.

19. Coloured. Age 27. Old worker. P., + 33 pounds. T.u.P., 8 hours. T.o.D., 10 minutes for first, 18 minutes for second lock; total, 28 minutes.
Symptoms (1½ hours after decompression).—Dizziness, followed soon by unconsciousness and convulsions.
Treatment.—Died while being recompressed.
Died 15 minutes after attack.
Autopsy Findings.—Coroner's case. Dr. Keays present. Subcutaneous emphysema along great veins. Gas under tension in right heart and generally throughout the venous system. Heart and other viscera normal. Aorta narrow, thymus persistent, hyperplasia of lymphoid tissue in spleen, intestines and mesenteric lymph-nodes.

20. German. Age 28. New worker. P., + 29 pounds. T.u.P., 2 hours (2 hours outside); total, 4 hours. T.o.D., 10 minutes for second lock; total, about 15 minutes.
Symptoms (30 minutes after decompression).—Pains in legs, dizziness, vomiting, weakness, mottling on body.
Treatment.—Recompressed twice, with some improvement first time, none second time.
Died 14 hours after attack.
Autopsy Findings.—Coroner's case. Was unable to get report.

Von Schrötter has summarized 137 fatal cases (1854-1897), and places them in two groups—firstly, those which exhibited central nervous symptoms and died from secondary complications after some days, weeks, or months; secondly, those which died very soon after decompression. In the first group there were 36 cases, on 26 of which autopsies were made; in the second group 70, with 27 autopsies, of which only 18 were properly reported.

In the 20 autopsies of the first group lesions of the spinal cord were found, such as disseminated or localized myelitis, hæmorrhage in the meninges and cord, together with complications, such as cystitis, pyonephritis, bedsores, etc.

Of the 18 autopsies properly reported of cases which proved fatal rapidly, 11 showed the presence of free gas in the circulatory system. In the other 7 cases there was congestion of the lungs, liver, etc.; in some a condition resembling suffocation.

Of the 14 cases reported by Keays, and belonging to the second group, details of the autopsies of 12 were obtainable, and 8 of these showed free gas in the circulation.

In Holland * regulations have been passed enforcing a slow rate of uniform decompression, thus—

+ 1 atmosphere, 15 minutes.
+ 1·5 atmospheres, 22·5 minutes.
+ 1·5 to 2·0 atmospheres, 22·5 to 32·5 minutes.
+ 2·0 to 2·5 atmospheres, 32·5 to 42·5 minutes.
+ 2·5 atmospheres, 42·5+ 2 minutes per $\frac{1}{10}$ atmosphere.

The result of this, at the Westelijke Viaduct Works, Amsterdam, has been to abolish all grave cases in which life is threatened, but to make little difference in the matter of "bends." The maximal pressure here was +2 atmospheres. In one group of 108 men there were 55 cases, 7 of which were ear trouble, 3 paresis, 1 Ménière symptom complex, 3 vertigo, 1 sudden deafness, and the rest "bends." Only 1 case left any permanent trouble; nearly all were relieved under twenty-four hours.

In a second group of 103 men there were 44 cases, 1 of which was ear trouble, 1 paresis, 1 (or 2 ?) Ménière, 1 vertigo, and the rest "bends." Recompression was used as the method of cure, and was effectual in most of the cases. Sometimes the pain returned after the first recompression in spite of slow decompression, and the treatment had to be repeated with a still slower rate of decompression—*e.g.*, 60 minutes from + 1·8 atmospheres.

The influence of the rising pressure on the case incidence is shown by the following. The shifts at the highest pressures were few.

Group I.		Group II.	
Atmospheres.	Cases.	Atmospheres.	Cases.
+ 0·6	1	+ 0·9	1
+ 0·8	1	+ 1·3	2
+ 0·9	1	+ 1·4	3
+ 1·0	1	+ 1·5	4
+ 1·5	2	+ 1·6	14
+ 1·6	7	+ 1·7	12
+ 1·7	14	+ 1·8	24
+ 1·8	19	+ 1·9	34
+ 1·9	26	+ 2·0	5
+ 2·0	13	+ 2·2	1

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* "Verslag van de Ambtsbezigheden van den Medisch Adviseur bij de Arbeidsinspectrie," 1905-1906.

The influence of age by these figures :

GROUPS I. AND II.

Age.	Workers.	Cases.	Percentage.
20 to 30 years ..	110	49	44·5
30 to 40 years ..	67	41	61·0
40 to 45 years ..	11	6	54·0

Caisson workers are exposed to other risks besides that of decompression—to the ordinary accidents of their work ; the possible fouling of the works with poisonous gases, such as carbon monoxide and hydrogen sulphide ; the sudden inrush of water from careless manipulation of air-locks, or " blow-outs " ; and the bursting of the caisson.

During the building of a pier at Havre, a door leading into the caisson was opened at the wrong time, and water rushed in and drowned one of the workmen,* the others escaped with difficulty. Such accidents are prevented by having competent men to control the air-locks.

To minimize the danger of " blow-outs " screens are arranged which resist the rise of the water, the air being compressed into the upper parts of the caisson or tunnel ; the men, escaping into these air-locks, can pass along them and reach the shaft. Caissons have burst on several occasions.

An explosion occurred at Douchy when eight men were in the caisson† four were crushed to death, two others, having started to climb the ladder to escape, fell down, no one knows why or how, the seventh suffered no harm, the eighth was floated up by the water and also escaped. The engineer suggested that the specific gravity of this man's body was lightened by the compressed air in his body !

Triger, while investigating the effect of compressed air on himself, suffered instantaneous decompression. There was a loud report, and he found himself in icy coldness and obscurity of a thick fog—the glass window had blown out. The manometer at the moment indicated 40 inches, a little over 2 atmospheres. Nothing worse than the surprise ensued.

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* *British Medical Journal*, 1909, i., p. 260.

† *Compte rendus, Ann. des Mines*, 1847, 4th Series, tome xi., pp. 121-148. Cit. after Bert.

In 1859 there was an explosion in a caisson used in sinking the piles of a bridge at Bordeaux. The depth of water was not more than 12·9 metres—a little over 2 atmospheres absolute. Seven workers were unaffected, two were killed by the violence of the explosion.

A bridge caisson at Chalonnes* exploded (1865). The depth was 14 metres. The two workers were almost instantly killed, no doubt by violence. The lung showed interlobular and vesicular emphysema in numerous places. The blood contained some bubbles of gas.

At Hepburn (1908), after four men had been working for nearly two hours in a pressure of + 30 pounds, the caisson burst. The man at the bottom was killed by violence, the other three, although bruised about the head and limbs, *in no way suffered as a consequence of the immediate decompression.*

There is a tale told of a man who was actually blown through the silt from the original Hudson tunnel works into the river, and was picked up alive and unharmed. The late Sir Benjamin Baker told of Chinamen setting up the air-lock doors of a caisson in China the wrong way on, and of a man being blown through the lock into the river.

The Grecian sponge-divers made a habit of "blowing up" themselves in a few seconds, and generally escaped without harm after their short stay at the bottom.

To compare with these, I cite an experiment of Bert. A dog had been exposed for one hour to $+9\frac{1}{2}$ atmospheres. When the chamber exploded, death was instantaneous. There was enormous emphysema, both subcutaneous and submuscular. Gas in the belly, in the epiploön, in the anterior chamber of the eye, in the cerebro-spinal fluid and spinal cord. No hæmorrhages in the cord, brain, or lungs. No gas in the left heart, but the right full of gas (CO_2 15·2, N 82·8, O_2 2 per cent.). Dogs can be decompressed very rapidly from pressure even up to +4 atmospheres without suffering harm.

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* P. Bert, *loc. cit.*, p. 401.

CHAPTER VI

LESIONS OF THE SPINAL CORD

We have seen that the rate at which different animals, and different organs of the same animal, become saturated and desaturated in compressed air, is proportional to the volume of the blood relative to that of the tissues and the velocity of the circulation. We have seen, too, that when a liquid saturated with gas under pressure is suddenly decompressed, the excess of gas does not instantly all come out of solution either by bubbles or diffusion. This delay is especially marked in the colloidal bodily fluids. If the activity of the circulation is great enough, the excess of gas may, by diffusion through the lungs, escape without formation of bubbles. It is to be expected, therefore, that the distribution of the bubbles in the bodies of animals submitted to a rapid decompression would vary with the activity of the circulation in the different parts. Thus bubbles are not found in gland cells or muscle fibres, but may occur, on the other hand, abundantly in the collections of body fluids—bile, urine, synovial and amniotic fluid. Bubbles are found most frequently in the fat, because fat absorbs five times as much nitrogen as water, and the circulation through the fat is relatively poor.

The white matter of the central nervous system is fatty in nature, and it, too, has relatively to the grey matter a poor circulation, hence this is a seat of predilection for bubble formation, and the bubbles form in those parts of the central nervous system which are least in functional activity, and therefore have the most sluggish circulation. A. E. Boycott and G. C. C. Damant have made an exact study of the distribution of the bubbles in the spinal cord of ten goats, and conclude that—

"1. Bubbles are clearly much more abundant in the white than in the grey matter—in several cases about five times, making allowance for the much greater bulk of the white matter.

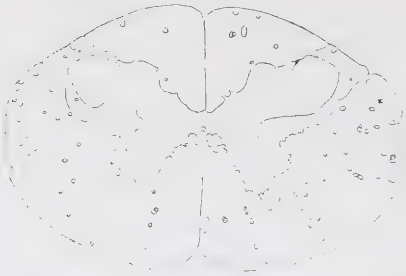

FIG. 37.—BUBBLES IN SPINAL CORD OF GOAT AT LEVEL OF DECUSSATION OF PYRAMIDS (BOYCOTT AND DAMANT).

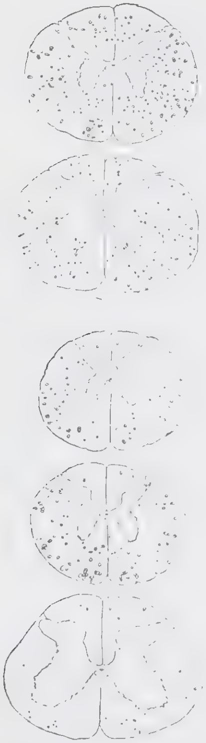

FIG. 38.—BUBBLES IN SPINAL CORD OF GOAT AT LEVEL OF SECOND CERVICAL, SIXTH CERVICAL, FIFTH DORSAL, SECOND LUMBAR, FIFTH LUMBAR ROOT (BOYCOTT AND DAMANT).

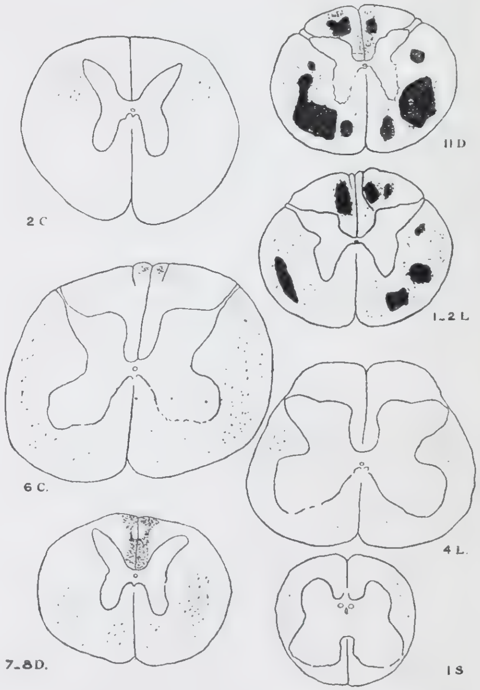

FIG. 39.—SPINAL CORD OF GOAT (BOYCOTT AND DAMANT).

Necrotic areas in the region of eleventh dorsal to second lumbar roots. Ascending and descending degeneration is shown in the sections above and below these areas.

Those that occur in the grey matter are localized especially close to the edge, and in many cases bubbles are more abundant in the deeper parts of the white matter than nearer the surface. This distribution may be correlated with the blood supply: the grey matter has a particularly good, and the white matter a particularly poor, circulation. The blood supply of the grey matter may be described as central in origin, and reaches its minimum towards the junction of grey and white matter, where also the peripheral white matter vessels end. We do not know by any direct evidence that the circulation in the posterior columns is so much better than that in the antero-lateral columns as to account for the fact that bubbles are fully twice as abundant in the latter.

"2. As regards different segments of the cord, it is equally clear that bubbles are least frequent in the lumbar enlargement and most abundant in the dorsal and upper lumbar cord. It may be surmised, with a considerable degree of probability, that the circulation in different regions of the cord is proportional to their functional activity, and that, therefore, the cervical and especially the lumbar enlargements are much better supplied with blood than the more passive segments. In this connection we may mention that we have, except in the special case of Goat 3, found no bubbles in the medulla or pons (which have been thoroughly and systematically searched) or in the cerebral hemispheres (which have been less completely examined).

"3. Several of the cases detailed show a marked relation between the occurrence of bubbles and the incidence of necrosis of the white matter. This necrosis is due to the blocking of the circulation by intravascular bubbles, and in these areas, therefore, bubbles would be particularly liable to form, as the excess gas could not be carried off from the tissues by the blood.

"In our goats a lasting paralysis appeared to be in all cases due to softening in the cord. This necrosis was confined to the central portions of the white matter; no alteration in the periphery of the white or in the grey matter was found in any case, and though all the cases were not examined from this point of view, no definite changes in the cells could be made out (method of Nissl). The longitudinal distribution is shown in the table on p. 96:

Number of Goat.	Sex.	Weight in Kilos.	Pressure Lbs. +	Exposure Minutes.	Decompression Minutes.	Distribution of Necrosis.			Killed after Days.
						Segments.	Length in Inches.	Columns.	
XXVI.	M.	18	75	55	11	11 D. to 1 L.	3	lat. and post.	12
XV. ..	M.	17	75	18	31	6 C. to 11 D.	9	lat. and post.	69
4. ..	M.	20	45	120	$\frac{1}{2}$	4 D. to 8 D.	$3\frac{1}{4}$	ant.-lat. and post.	1
XVA. ..	F.	15	45	120	$\frac{1}{2}$	9 D. to 2 L.	$4\frac{1}{2}$	lat. and post.	1
XXIIIA.	F.	26	45	120	7	8 D. to 2 L.	5	lat. and post.	6
XVIA.	M.	21	45	120	$\frac{1}{2}$	1 C. and 3 L.	—	lat.	12
XIIIA.	F.	28	45	120	10	1 C.	—	post.	3
						2 D. to 2 L.	—	lat. and post.	
XA. ..	M.	17	75	13	1	10 D.	—	lat. and post.	4

"These results indicate a special incidence of this softening on the lower dorsal and upper lumbar cord. This distribution is doubtless to be explained on the ground that the circulation through the cord is less active in these segments than elsewhere, and corresponds to that of the thrombotic lesions—so-called myelitis—in man. It is remarkable that in no case have we found evidence of infarction in any tissue except in the white matter of the cord and in fat.* It is clear that a number of bubbles are passed through the lungs and distributed by the arteries (where they may be found in abundance) ; but these emboli never appear to produce necrosis unless the tissue in which they lodge is of a fatty nature, and infarcts of, *e.g.*, spleen or kidney have not been seen. It may be supposed, therefore, that the bubbles do not form effective emboli unless they increase in size *in situ* by accretion of fresh gas from their surroundings. The escape of the grey matter may be attributed to its free circulation ; the amount of fatty stuff in it is not materially less than in the white matter. We obtained no evidence of softening in the parts above the spinal cord, either by direct examination or from the occurrence of secondary degenerations. In two cases necrosis was found post mortem in animals in which no lasting paralysis had been observed during life. In one this was situated by the lateral columns in the seventh dorsal segment of an animal which had had an attack of paraplegia, lasting only two hours, forty-three days ante

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* Embolism on a massive scale is seen in the lungs and liver. In the former it produces immediate death ; in the latter it may be the cause of some of the obscure general symptoms and delayed deaths which occasionally occur.

mortem, and 'bends' seven times. In the other patches of necrosis were found in the lateral and posterior columns at five dorsal and four lumbar; this goat had had an attack of double hind-foot drop lasting forty minutes, fifteen days before death and 'bends' five times. We obtained evidence in other cases that these attacks of temporary paralysis do not necessarily leave any traces of injury to the cord."

P. Bert, Catsaras, Blanchard, and Regnard all figure the necrosis of the cord following stoppage of the circulation by bubbles. Von Leyden supposed that hæmorrhages occurred from rupture of the capillaries by bubbles of nitrogen. Von Schrötter established the necrosis as due to blockage of the bloodvessels by bubbles either in them or in the white matter, and that rupture of bloodvessels may lead secondarily to hæmorrhages. The gas dissolved in the white matter can escape into the perivascular spaces, or into the periaxial and perimyelin spaces of the nerve fibres.

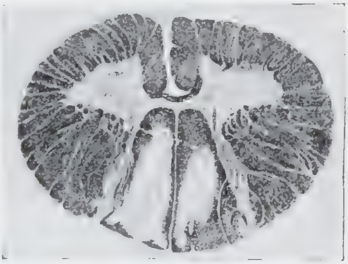

FIG. 40.—NECROTIC AREAS IN POSTERIOR COLUMNS OF CORD FROM A FATAL CASE OF COMPRESSED-AIR ILLNESS (VON SCHRÖTTER).

The brain has a much better circulation than the spinal cord, and the grey matter a far better circulation than the white. The cervical cord receives a good supply of blood from the anterior spinal artery and its tributaries. In the dorsal cord the arteries are slender, and there the lesions generally are found. In seven post-mortems collected by von Schrötter there were found seven areas of necrosis in the cervical cord, thirty in the dorsal, and nine in the lumbar. In Fig. 41 is shown the remarkable compression of the brain cells by bubbles of oxygen, produced by rapid decompression after exposure to 8 atmospheres of oxygen. The mice were convulsed, and had a series of convulsions after decompression. Some were killed for examination, the others recovered completely next day. The oxygen allowed the cells to live until it was absorbed and the circulation re-established.

The local necrosis is followed by degeneration of the nerve fibres, which are cut off from their nerve cells, and thus the pathways of nervous conduction are interrupted, and paralysis occurs. Bubbles in the ordinary fat of the body are like stones scattered in the surrounding fields, while bubbles in the white matter of the cord may be compared to rocks thrown down on the railway-lines of London.

Besides immediate recompression, there is little to be done for those paralyzed after decompression. In cases of paraplegia the power to control the evacuation of urine and fæces is usually lost or impaired. The sufferers get bedsores, also bacterial infection of the bladder, and secondarily of the kidneys, which results from the constant dribbling away of the urine. The bedsores and the renal infection lead to the exhaustion and death of the patient. Good nursing in a hospital is all that can be done for him.

FIG. 41.—BUBBLES OF OXYGEN IN BRAIN OF MOUSE.

CHAPTER VII

THEORIES AS TO THE CAUSE OF COMPRESSED-AIR ILLNESS

THE theories put forward concerning compressed-air sickness have been based largely on erroneous conceptions and lack of knowledge of physical laws. The blood has generally been supposed to be driven into deeper parts, and to suddenly revulse and produce lesions on decompression. By others the excess of air has been supposed to increase the rate of oxidation of the body tissues, and on decompression the body is left with accumulated waste products—ashes choking the furnace no longer supplied with an air-blast. The true theory has been long in coming to the proof—viz., that nitrogen dissolved in the body under pressure forms bubbles on sudden decompression, and so obstructs the circulation.

Musschenbroeck (1755),* submitted animals in enclosed vessels to air compressed to three times the pressure of the atmosphere, and found they lived longer under these conditions than in the same vessel filled with air at atmospheric pressure. The animals were quite lively and well if compressed only for a short time. He concluded that some poisonous substance is exhaled into the air, "since it is difficult to conceive that anything necessary for life is taken up from the air and mixed with the blood, the arguments of the celebrated M. Boerhave having proved that air cannot pass from the pulmonary vesicles into the blood." The opinion of an illustrious contemporary Haller,† was that compressed air at too great a depth kills the men exposed to it (in the diving bell) by stopping respiration, and offering such a resistance to the heart that the circulation is suppressed. He is the first to set forth an erroneous mechanical theory, which has been widely held since. The divers really lost their lives from suffocation.

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* Cit. after Bert, "La Pression Barométrique," p. 461.

† "Elem. Physiol. Corp. Humani," 1761, vol. iii.

In 1801 Citoyen Achard* exposed birds to air compressed to a quarter of its volume. They remained lively for an hour. Animals lived five times longer in a receiver in which the air was made three times the density of the atmosphere than in the same receiver filled with air at normal pressure. Sudden compression, he says, threw the animals at first into a state of inaction and lethargic sleep !

The active imagination of Brizé Fradin† made him declare that the compressed air opened up the lungs and the angles formed by the pulmonary vessels, made the circulation more rapid, increased the *frottements intimes* of the muscle, and the production of heat.

Jaeger‡ asserted that highly compressed air caused sudden death by producing apoplectic hæmorrhage, and stopping the return of blood to the heart and upper parts.

Poiseuille § carried out experiments of fundamental importance, constructing a chamber fitted with glass windows, in which he could view microscopically the circulation in the transparent parts of salamanders, frogs, tadpoles, very young rats, and mice. No change occurred when the pressure was quickly raised 2, 3, 4, 6, and 8 atmospheres. The young of rats and mice (in the first day of life such young are able to live some hours without breathing) exhibited the circulation in full integrity when the chamber was evacuated, "thus showing how erroneous was the opinion of those who held that the circulation was impossible when unsupported by the barometric pressure. It is not to be denied that the barometric pressure acting concurrently with the movements of respiration aids the circulation." Poiseuille himself demonstrated that this was so.

Unwitting of Poiseuille's experiments, Pol and Watelle were led away by the congestion of the lungs and other viscera found in the two fatal cases examined by them, and concluded that just as rarefied air leads to bleeding outwardly, so compressed air must cause congestion inwardly—*contraria contrariis.*

How, then, to explain the fact that the illness occurs after decompression ? The congestions, they said, are rendered

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* *Ann. de Chimie*, 1801, tome xxxvii. Cit. after Bert, p. 461.

† "La Chimie Pneumatique Appliquée aux Travaux sous l'Eau," Paris, 1808. Cit. after Bert.

‡ "Tractus Physico-Medicus de Atmospherâ et Aere Atmospherico." 1816. Cit. after Bert.

§ *Comptes rendus, Acad. des Sciences*, 1835, i. 554.

harmless during compression by the superoxygenation of the blood.

Hoppe-Seyler,* from the result of observations on animals submitted to sudden rarefaction of the air, was the first to lay down the correct doctrine that, "if, after submitting an animal to compressed air for some time, one suddenly diminishes the pressure, there will not be time for the gas to escape from the venous blood in the lungs. This is why," he says, "in the mines of France, sudden deaths have taken place, and no anatomical lesions have been found." His conclusion was drawn from analogy, not from direct experiments with compressed air. Hoppe had his vacuum pump and chamber to hand, but no compressed-air chamber, and settled the business to the satisfaction of himself by the simpler means of sudden rarefaction.

François,† discussing the effects on the workers at the Kehl Bridge, wrote: "Air amalgamates with the cellular tissue just as mercury amalgamates with zinc, so that no molecule of the metal is visible to the naked eye." This air, stored beyond measure in the tissues, will seek to equilibriate itself with the surrounding atmosphere, and the more rapidly, the quicker the decompression. The pathological effects are due to this, and not to superoxygenation, as has been suggested.

Respiratory troubles are, he says, due to pulmonary congestions; there is a cupping effect from the sudden fall of pressure in the lung. Nervous troubles are likewise congestive phenomena. François evidently formed no clear and definite conception that these symptoms were all caused by air embolism. Bucquoy ‡ also observed the workers at Kehl, and pointed out that the blood-corpuscles do not absorb more oxygen from compressed than from free air, because the proportion of oxygen combined has been demonstrated to be within limits independent of the pressure of oxygen. The red colour of the venous blood, which has been observed in all compressed-air workers, is due, then, to the oxygen dissolved in the plasma; either the tissues use oxygen directly, or the blood-corpuscles take it up when they yield oxygen to the tissues. Bucquoy is not equally sound in his views concerning the distribution of pressure in the body. He thinks that the superficial blood transmits the pressure to the

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* Müller's *Archiv*, 1857, pp. 63-73.

† *Ann. d'Hyg. Publ. et de Méd. Lég.*, 1860, 2^e série, tome xiv., pp. 289-319. Cit. after Bert.

‡ "De l'Air Comprimé Thèse de Strasburg," 1861. Cit. after Bert.

blood almost equally everywhere, but that the superficial tissues bear off some of the pressure, and do not fully transmit it from layer to layer to the deeper parts. Hence the bloodvessels become congested in the deeper parts, and hence the congestions and hyperæmias, of which all writers speak.

In the matter of solution of gas in the blood he puts forward far-seeing views. "If a man goes into compressed air, the oxygen, carbonic acid, and nitrogen in simple solution in the blood ought to augment with the pressure; if the compression has lasted long enough, according to the law of Dalton, the volume of each gas absorbed by the blood ought to be proportional to its pressure in the condensed air. . . . During and after decompression all the excess of dissolved gas in the blood tend to escape, and the exposure to the compressed air being equal, the more forcibly the higher the pressure." The conditions are much the same as when one opens a soda-water bottle, and sees how rapidly the bubbles of dissolved CO_2 escape. The particles of free gas spread throughout the vascular system remain mechanically mixed with the blood, and, increasing its volume, distend the vessels—hence, hæmorrhages threaten, and there is a general tendency to emphysema. Bucquoy observed the case of a worker who suffered cruelly in the knee. Dry cupping glasses placed round the joint fell off one after another, although placed by a skilled attendant. They were put on many times, and when they held at last the patient said he was much relieved. This observation is explained by the supposition that there was liberation of free gas in the tissues of the knee. Bucquoy ends by advising the engineers to take every precaution to make the decompression sufficiently slow.

Hermel[*] suggested that the illness was due to the vitiated air in the caissons, and that the red blood in the veins was due, not to excess of oxygen, but to carbon monoxide! Foley[†] contradicted all other authors on two points: first, "workers who prolong their stay in compressed air over twelve hours will be immune to trouble or decompression because '*la réaction nervose-sanguine est générale*,'" whatever he may mean by that; secondly, he tells the workers to hasten the decompression as much as possible, to avoid the icy coldness of the air-lock. He developed theories of vascular reaction which have no basis in physical

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[*] *Art Médical*, 1862, xvi., p. 428; 1863, xvii. 27, 105, 194. Cit. after Bert.

[†] "Du Travail dans l'Air Comprimé," Paris, 1863. Cit. after Bert.

facts. Babington and Cuthbert,* reporting the cases at Londonderry Bridge Works, surmised that the brain and cord, shut as they are within rigid bony cavities, cannot follow the changes in atmospheric pressure as quickly as other and more elastic parts. Panum† puts down as "wholly unphysical" a suggestion made by Standahl that the compressed air diminishes the volume of the blood by diminishing that of the gas it contains. Panum states clearly that the morbid phenomena are due chiefly to dissolved air, set free in the vessels as bubbles of gas which cause embolic obstructions in diverse parts. He investigated the effect of compressed air on the manometric record of blood pressure in two dogs, and found none.

Leroy de Méricourt‡ is equally clear in assigning the cause of the illness of divers to air embolism. "The greater the depth and the longer the stay at the bottom, the more will the blood be charged with an excess of gas in solution. The diver is really, from a physical point of view, in a condition like to a bottle of water charged with carbonic acid."

"Experimenters who make intravenous injections into horses know that if they allow a bubble of air to pass in, the animal falls as if struck by lightning, and at the very moment when the bubble reaches the cerebral circulation. This sideration is only momentary, but if a quantity of air is introduced, death rapidly takes place." In spite of the clarity of his conception, Leroy de Méricourt cannot quite get away from the incompressible nature of the cranio-vertebral cavity having something to do with the production of hæmorrhages there.

Bouchard § throws physical laws to the wind when he conceived that as the intestinal gas became compressed the abdominal walls caved in, and the latter resisted this displacement and so acted as a gigantic cupping glass, drawing the blood into the viscera. On decompression the opposite took place, and blood driven from the abdomen produced hæmorrhages in the lungs, cord, etc. Gal, following the absurd doctrines of Foley, expresses curious ideas concerning the sensations, which, he says, are perceived less clearly by the organs of sense in compressed air, and therefore the brain and cord, less excited, pro-

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* *Dublin Quarterly Journal of Medical Sciences*, 1863, xxxvi., pp. 312-318.

† *Pflüg. Arch. f. Physiol.*, 1868, i. 125-165.

‡ *Ann. d'Hygiène Publique et de Médicine Légale*, 1869, 2e série, xxxi., 274-286.

§ "De la Pathogénie des Hémorrhagies," Paris, 1869. Cit. after Bert.

duce less nervous force. In consequence "l'influence du grand sympathique" on the nutrition of the tissues is enfeebled. So long as the worker has not exhausted his reserve of nervous force he will escape; but one day this will come about, and he, weakened, will fall a victim to rapid decompression. He attributes the ill-effect of this to "want of reaction on the part of the tissues," whatever that may mean, and possibly to the setting free of gas, as Bucquoy and Leroy de Méricourt suppose.

Gal laid down the following rules:

Depth.	Work.
Up to 25 metres	1½ hours
,, 30-35 ,,	½ hour
,, 35-40 ,,	¼ ,,

The French divers do not go beyond 35 metres; the Greeks, he says, venture to 54 metres (175 feet). Not only should the duration of work be diminished, but that of decompression should be augmented. He suggests half a minute per metre, but the divers, he says, will not submit to this, and ascend about 4 metres per minute.

Bauer* (1870) supposed that under the influence of the superoxygenation there is an increased combustion of the tissues. This does not harm while one is under compression, but on decompression the excess of waste materials poisons the system —a theory which has been revived by a distinguished engineer in recent years. Every physiological fact is against it.

The American physicians generally took up erroneous mechanical views of the cause of the illness. Thus, A. H. Smith, discussing the cases which occurred at the Brooklyn Bridge Works, says: "Under high atmospheric pressure the centres will be congested at the expense of those more compressible; structures within closed bony cavities are congested at the expense of all others; firm and compact structures will be congested at the expense of those more compressible. The skin and superficial structures will be anæmic. The central portion of the limbs and the anterior organs of the body will be especially engorged on account of both situation and structure. The brain and spinal cord, and the interior of the shaft of the long bones, will be congested to a high degree. . . . These changes are not perfected until a considerable time has been passed in the compressed air. . . . The blood is distributed, not in accord-

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* *St. Louis Medical and Surgical Journal*, 1870, No. 3.

ance with the physiological demands of the different parts, but in obedience to overpowering physical force." On "locking out" "it is not to be supposed that the vessels will instantly assume their normal condition. They are in a state of relaxation, not only in the congested but also in the anæmic parts. The capillaries being clogged with effete blood, the nutrition of the part must suffer, and disturbances of function will result."

Smith knew of Bert's experiments probably only in abstract, and rejects the air embolism theory built upon these experiments, because Bert obtained evidence of air embolism in animals decompressed from higher pressures than +3 atmospheres, while caisson workers are affected at lower pressures than this.

"The presence of bubbles of gas in the vessels," he says, "is a condition which the system could never learn to tolerate by frequency of repetition."

Thus he is led to set up an astounding theory, to wit, "the vasomotor function is entirely superseded and the muscular coat of the vessels thrown completely out of use. The vessels are as passive as the water-pipes of a house!"

"Blood having been forced into the cranium and spinal canal, with a pressure of 30 or 40 pounds (!) has continued to circulate, it is true, but only because the whole vascular system was subjected to the same pressure. But now (on 'locking out') there is a sudden removal of the pressure from the soft parts, resulting in a great increase in the vascular area. . . . The vessels in the bony cavities do not readily participate in this changed condition . . . hence, slowing of the current or, perhaps, actual stasis . . . thrombi may have formed, affording material, perhaps, for emboli at more distant points," and so on—the veriest moonshine, the riot of an imagination wholly ignorant of elementary physical laws.

The English physician Moxon, in his "Textbook of Medicine," and the Greeks, N. Paritsis and Tetzis, likewise put forward the mechanical congestive theory, which in one country or another has gained wide acceptance, so slowly has the magnificent work of the French school gained recognition.

Moxon * wrote: "The pressure drives the blood from the surface and probably lessens the amount in all vessels to which its influence extends. . . . The paralysis is due, perhaps, to an acute revulsive anæmia of the cord."

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* Croonian Lectures, *British Medical Journal*, 1881, i.

Corning[*] (Hudson Tunnel, 1890), following the views of Smith, goes so far as to say, "At one time it was believed that, on leaving the condensed atmosphere, there was a development of gas from the blood which caused a rupture of the neighbouring tissue. It has been urged, however, in rebuttal, that the limitation to the dorsal portion of the cord and the infrequency or total absence of vascular hæmorrhages, are totally opposed to this theory."

James Hunter[†] (Forth Bridge, 1890) says, "There is, for mechanical reasons, an intropulsive effect on the cutaneous circulation, with an absorption of gases by the liquids of the body. . . . If decompression is made too rapidly, there is a great giving out of heat, producing an extremely devitalizing effect on the workers. There is a loss of balance between oxygenation and tissue waste, which held during the increased vitality of compression, and there is a sudden liberation of the gases, which had been absorbed, and which now tend to interrupt the circulation, causing severe pain in the neighbourhood of the vascular fringes of joint surfaces." Hunter, with a liberality of mind, accepts a little from every theory advanced.

Von Rensselaer[‡] (Hudson Tunnel) argues for a congestion of the nervous system on compression, followed by anæmia on decompression. Unsupported by any experimental evidence, he declares that gas bubbles can only be set free if the decompression is completed in half to one minute. He rightly concludes that long exposure, high pressure, rapidity of "locking out," cooling during "locking out," and fatigue, are all important factors; rightly points out that fatness, age, alcoholic excess, heart and kidney disease, defective nutrition, are predisposing causes. He knows that the lesions in the cord in most of the cases of paraplegia consist of a disseminated myelitis with destruction of nerve fibres, bloodvessels, and neuroglia of the white substance, especially in the posterior and postero-lateral parts, with consequent ascending degeneration in Goll's tract, and descending degeneration in the pyramidal tract; that the grey matter is undamaged; that the dorsal cord is the seat of selection because of the slender vascular supply there.

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[*] *New York Medical Record*, xxxvii. 513-521.

[†] "Compressed Air," etc., thesis for M.D., Edinburgh.

[‡] *New York Medical Record*, 1891, x. 141-175. Transactions of the Medical Society of New York, 1891, pp. 144 and 408. Cit. after v. Schrötter.

G. Thompson* (1894), while accepting the mechanical congestive theory, supposes that the excretion of CO_2 against increased atmospheric pressure is rendered more difficult. All these American authors were wholly neglectful of the detailed experimental work of the French School. They spin unsubstantial theories, unsupported by physical laws, and contrary to the published experiments of eminent European physiologists. It is fortunate that whatever their theories, experience demonstrated that slow decompression prevents, and recompression cures. Von Cyon † (1897), most erratic of physiologists, and old antagonist of Bert, upheld the theory not only that compression of the peripheral vessels takes place, but the pressure in the cerebral vessels, confined as they are within the skull, does not come quickly into equilibrium on decompression. So long ago as 1808 Brizé Fradin had contradicted such erroneous views. Poiseuille had carried out his fundamental observations on the circulation. Giraud Teulon,‡ too, in 1857, very properly insisted that the pressures exerted on the human body by the surrounding atmosphere "se combattent, mutuellement et se détruissent d'une manière parfaite." The fluids of the body are incompressible, and transmit the pressure instantly and equally to all parts.

Regnard§ produced, perhaps, the most crushing refutation of these theories when he pointed out that the drag-net shows us that life is teeming in the abysms of the sea, where the pressure is 200 atmospheres or more.

M. Gruber|| pointed out that no one has observed changes supposed to take place in the circulation—blanching of the face, lips, etc., on "locking in," and congestion on "locking out." "The whole mechanical theory rests on wrong physical conceptions. The body is partly fluid, partly semi-fluid, and transmits the pressure instantly to the inner parts, so that the circulation is unaffected. If a manometer were put in connection with the eye, the intraocular pressure must show the same positive pressure, for otherwise the bulb would be deformed. On passing from 1 to 2 atmospheres the absolute pressure is doubled both in and outside the eye ; the difference between the two

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* *New York Medical Record*, 1894, xiv. 133.

† Cit. after Heller, Mager, von Schrötter, p. 383.

‡ *Compte rendus, de l'Acad. des Sciences*, 1857, xliv. 235.

§ "La Vie dans les Eaux," Paris, 1891. "Le Cure d'Altitude," Paris, 1890.

|| Cit. after Heller, Mager, and von Schrötter.

pressures remains the same. It is only the intestinal gas which can expand suddenly on rapid decompression and drive blood out of the abdominal viscera into the lungs and brain." Pressure only affects the circulation when it is applied unequally to the body, as when a diver goes under water clothed in a leather dress, with a pipe opening on the surface.

A few writers have particularly laid insistence on the ill effects of cooling and fatigue. Thus Jaminet* (St. Louis Bridge) writes: "The exhaustion of the system under certain circumstances has been, with a very few exceptions, the cause of what has been called 'bridge cases.' . . . Paralysis is but the result of reflex action caused by the spontaneous refrigeration of the whole system," and so on. Tinc (Felesti-Cernavada Bridge, 1891-1893) also lays great stress on excessive work, rapid change of temperature, and, above all, on poisonous gases arising from combustion of candles, etc. Asphyxial cases, he supposes, are brought on by the damage inflicted on the lungs by the sooty atmosphere!

There can be no doubt that fatigue, arising from hard work in hot, moist, ill-ventilated caissons, is a predisposing cause, for the vigour of the circulation and respiration is slackened thereby during the "locking out." The cold on "locking out," by constricting the cutaneous vessels, also impedes the circulation therein and the removal of dissolved nitrogen from the peripheral parts. Jaminet and Tinc were right in their insistence on the harmful effect of fatigue and cold, but wrong in their theoretical concepts.

Hoppe-Seyler, by exact experiment, demonstrated the setting free of gas in the blood of animals submitted to rarefaction, and showed by analysis of the gas that it was chiefly nitrogen, with a little CO_2. Rameaux and Bucquoy, on the other hand, while correctly expressing the gas embolism theory, thought that the gas set free was CO_2.

P. Bert,† by a magnificent series of experiments, proved once and for all that "tous les accidents depuis les plus faibles jusqu'à ceux qui entraînent une mort soudaine, sont la conséquence du dégagement de bulles d'azote dans le sang et même dans les tissus quand la compression avait duré un temps suffisant."

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* "Physical Effects of Compressed Air," etc., St. Louis, 1871.

† "La Pression Barométrique," 1878.

The body of a workman exposed to compressed-air supports, according to calculations of Guérard, at +1 atmosphere an additional 15,000 to 20,000 kilogrammes; at +3 atmospheres an additional 45,000 to 60,000 kilogrammes; at +6 atmospheres an additional 90,000 to 120,000 kilogrammes. If it were not for the incompressibility of the fluids of the body, and the equal and instant distribution of the pressure to all parts, life would be impossible under any variation of atmospheric pressure. The mechanical theories of compressed-air illness are therefore ridiculous, on this consideration alone, not to mention the fact that life is found in the sea at depths corresponding to two or three hundred atmospheres.

It is neither CO_2 nor O_2 which plays the chief part, but nitrogen dissolved according to Dalton's law, which, once set free, on decompression may in one case block the pulmonary circulation, in another embolize the spinal cord, and so produce softening and paralysis there; in yet another produce swellings and emphysema in the tissues. "En effet, les tissus et toutes les collections liquides de l'organisme se sursaturent d'azote, et dans la décompression, ces gaz revenant à l'état libre distendent et même delacèrent les tissus au sein desquels ils se dégagent. De là, des productions gazeuses dans la tissu cellulaire, les liquides oculaire et cérébro-rachidien, dans la moelle, et où elles occasionnent des gonflements beaux et deviennent la cause de douleurs."

Bert exposed an animal to high pressure in an atmosphere poor in nitrogen and rich in oxygen, and decompressed it rapidly. In this case no nitrogen bubbles were found in the blood, for the oxygen can be rapidly absorbed by the tissues. It is the *partial pressure* of nitrogen, not the atmospheric pressure, which is the important factor. In striking contrast with this animal is the appearance of one decompressed in two to three minutes after exposure to +10 atmospheres of air. Bubbles of gas are to be seen everywhere in the vessels, the blood froths in the arteries and veins, in the portal vein, even in the vessels of the placenta and fœtus, if the animal is pregnant. The heart, continues to beat for some minutes, and drives the gas which is in the left ventricle, into the terminal branches of the arteries; it is seldom found, therefore, in the left ventricle. The venous circulation, which continues some little time, brings its store of gas bubbles into the right heart, and these collect there—in one cat to the extent of 33 c.c. The small amount of blood, still free from bubbles, finds its way through the patent pulmonary arteries into the left heart. Most of the pulmonary vessels are blocked with frothy blood, driven into them by the right heart.

Compare with this the case of an animal very slowly decompressed from +10 atmospheres. Few and small are the bubbles to be seen in it. The gas set free in its venous system passes the lungs with difficulty, and causes disturbance of respiration. It reaches the left heart in a state of such fine division that it can only be seen with the aid of the microscope. From thence the gas is driven into the arteries, and combines with that set free in the arterial blood—blood which has not had time to reach the veins. The gas bubbles may be reabsorbed without producing any effect, but if by unhappy chance they reach the capillaries of the central nervous system, symptoms result of irritation or paralysis, just as surely as (when the abdominal aorta is ligated) in the experiment of Stenon. If the bubbles vanish and the circulation is restored, recovery takes place.

Bert recognized that the bubbles do not appear immediately on decompression, but take time to form. He studied the softening which occurs in the spinal cord, and found bubbles in the softened part four days after decompression. The softening often follows so quickly that the affected part at the end of twenty-four hours may have the consistence of cream. This is due to autolytic ferments in the tissues.

He compared the varying effect of rapid decompression in different classes of animals and in individuals. The smaller animals—dogs, cats, etc.—are not seriously affected by rapid decompression from the lower pressures, and Bert studied his effects, using pressures of +5 to 10 atmospheres. This gave A. H. Smith and others grounds for refusing to apply the gas embolism theory to men who are affected after exposure to +1 or 2 atmospheres. The rapidity of circulation in relation to mass of body substance to be desaturated is the factor which makes the difference between small and large animals. Blanchard and Regnard, 1881, confirmed Bert's work by further experiments on animals, and, later, Catsaras, 1894, and Philippon. The last author substituted nitrous oxide for nitrogen in the atmosphere, and owing to its great solubility produced extraordinary tumefaction of animals on rapid decompression. Instantaneous decompression produced more powerful effects than a decompression lasting some seconds, in that the former caused actual rupture of pulmonary vessels and tissues. Evidence accumulated, and the air-embolism theory was supported by the results of post-mortem examination made in fatal cases of caisson illness. Hertwig, 1878, observed free gas bubbles in the vessels of a man who died at Limfiord Bridge. Von Leyden, 1878, and Schultze, 1879, put down to gas bubbles the lesions they found in the cords of two workers. Von Leyden supposed the bubbles tore the tissues.

Katschanofsky, 1881, records that gas bubbles were found in the blood of a dead diver.

Catsaras differentiated three forms of nervous lesion—the spinal, the cerebral, and the cerebro-spinal—and separated the spinal cases into lateral, postero-lateral, posterior, and transitory paralytic.

The characteristics of compressed-air illness are—(1) sudden invasion, (2) intensity of the symptoms at the very beginning of the invasion, (3) the polymorphic nature of the symptoms, (4) the usual and rapid recovery, (5) the symptoms once established nearly always retrogress; they hardly ever increase in severity.

Heller, Mager, and von Schrötter * confirmed Bert's work by experiments on animals; they demonstrated, as Bert did, the gas set free in the blood after rapid decompression, and determined by analysis the percentage of nitrogen set free in the heart, and established on a sure footing the air embolism doctrine for lower pressures than those studied by Bert. In their book they gathered a valuable store of information on the whole subject, a store to which the author and all other subsequent writers are greatly indebted.

One or other of my co-workers, J. J. R. Macleod, C. E. Ham, and Major Greenwood, and I, have brought forward the following evidence in disproof of the mechanical theory: (1) We enclosed a frog's heart in a small chamber with thick glass windows, and showed that it continued to contract in a normal manner at a pressure of even 50 atmospheres. Similarly, we showed that a frog's muscle could be excited to contract normally in like conditions. (2) In caterpillars, air is conveyed directly to the body cells by finely branching tracheæ. Their circulating liquid

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* "Luftdruck Erkrankungen," Wien, 1900.

is not respiratory in function. Sudden decompression from 27 atmospheres had no ill-effect on these, unless they had eaten leaves while under pressure. Then they were burst by the swelling of the swallowed air (Greenwood). (3) We enclosed a narcotized dog or cat in a pressure chamber, having first connected its carotid artery with a mercurial manometer, and set the manometer recording on a show clockwork drum, the manometer and drum both being put inside the chamber. We showed that the blood pressure and pulse-beats exhibited no noteworthy change on raising or lowering the pressure 2 to 3 atmospheres. (4) We contrived a chamber with glass windows, in which we placed a frog so that the web of its feet might be illuminated with an arc light and projected microscopically on to a screen. We found that the circulation in the capillaries did not alter when the pressure was raised quickly or lowered 20 atmospheres.

Proofs that Nitrogen Bubbles are the Cause of the Illness.—(1) By the same means we demonstrated both the setting free of nitrogen bubbles in the blood on decompression, and the fact that they can be again driven into solution by recompression—for on suddenly decompressing after a long exposure we had the keen pleasure of seeing the bubbles appear in the capillaries, grow in size and stop the circulation, to shrink and disappear again on putting up the pressure. This experiment was repeated by Sir Thomas Oliver.* (2) Macleod and I enclosed narcotized dogs in a pressure chamber, having first connected the carotid artery to a tap so that we could draw off samples of blood into a vacuum pump and analyze the blood gases. We then confirmed Bert's observations, and showed that the nitrogen dissolved in the blood varies with the partial pressure; roughly 1 per cent. of nitrogen is dissolved per atmosphere. By the same method we studied the giving off of nitrogen from the lungs during decompression. (3) C. Ham and I killed rats by rapid decompression from 10 atmospheres, and chopped up their bodies under water, collecting the gas set free in their bodies under a funnel full of water. We found 80 to 90 per cent. of the gas was nitrogen, and the rest chiefly carbon dioxide, with a trace of oxygen—*e.g.*, 10·7 to 16 per cent. CO_2, 2·1 to 4 per cent. O_2, 87·2 to 80 per cent. N_2. The gas obtained was more than there ought to have been according to the law of partial pressures and the volume of water in the

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* *Journal of the Royal Society of Arts*, May 11, 1906, vol. liv.

body. This excess we found was partly due to gas, swallowed or set free by fermentation, in the alimentary canal. Part of the excess, no doubt, was due to the greater solubility of nitrogen in fat, a fact then undiscovered. (4) We killed mammals by rapid decompression, and, opening the right side of the heart under water, analyzed the gas obtained, and showed it was 80 to 90 per cent. nitrogen, the rest being carbon dioxide, with only a trace of oxygen. The carbonic acid escapes from the blood because the nitrogen set free acts as a vacuum in regard to CO_2. The oxygen chemically unites with and is used up by the blood, and therefore is only found in small amount (confirmatory of von Schrötter). (5) Greenwood and I showed that rats and frogs, if submitted to high pressures of oxygen *until poisoned* by it, and then rapidly decompressed, have considerable amounts of dissolved oxygen set free in their bodies. This never occurs with low pressures of air, and oxygen bubbles are not a factor in caisson sickness. (6) We also showed that animals killed by decompression in 3 to 5 seconds from + 7 to 8 atmospheres have gas bubbles set free in the fat of the tissue cells, such as the liver and kidney, which actually vacuolize and disrupt the structure of the tissue cells. The liver and kidney may appear foamy with bubbles in such case. The fat, too, in all cases of rapid decompression, is honeycombed with bubbles, like whisked white of egg. Alveoli of the lungs, too, may be ruptured, and lobules rendered emphysematous by the violent expansion of the air within them. Much gas is set free in the alimentary canal, and in small animals, as the rat, within the peritoneal cavity. The bloodvessels are filled with columns of bubbles.

The Effect of very High Pressures of Water.

There is evidence of fish and other organisms living at depths of two or three miles in the sea. At a depth of 1,375 fathoms 200 specimens were captured belonging to no less than 59 genera and 78 species (*Challenger* Reports). At these depths it is quite dark, and the water is at 3° C. There is no vegetation, and the animals live on bacteria, débris that falls from above, or on each other. The fish are phosphorescent, probably to enable them to see the dead which fall down to them, and have capacious maws for securing the offal of the ocean. The following have been dredged from the "red clay" in all oceans : *

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* Canon Norman, President's address, Tyneside Naturalists' Field Club, 1881.

	Fathoms.
Pisces (4 species)	2440 to 2550
Mollusca (1 species)	2,600
Brachiopoda (1 species)	2,600
Tunicata (3 species)	over 2,300
Polyzoa (4 species)	,, 2,200 (1 at 3,125)
Crustacea (7 species)	,, 2,300

Paul Regnard* investigated the effect of water-pressure on various living organisms, and on the frog's muscle and heart. He found 400 to 500 atmospheres (2,200 to 2,750 F.) was a critical pressure which caused frog's muscle to swell and rupture, and live organisms to become " endormis." He studied the contraction of frog's muscle and the behaviour of small organisms by means of the apparatus shown in Fig. 43. The objects were projected on the screen by means of an arc light, and the lenses fitted in the chamber. The pressure was raised by an hydraulic press.

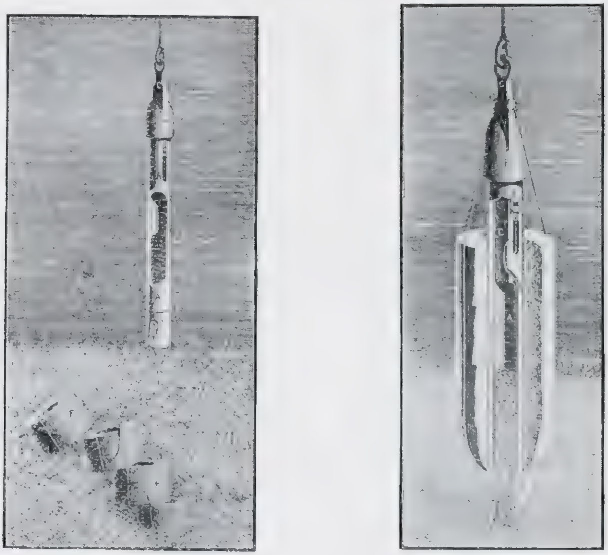

FIG. 42.—AUTOMATIC DREDGE FOR COLLECTING SAMPLE OF OOZE AT BOTTOM OF OCEAN (REGNARD).

The weights by falling off close the vessel.

The writer has reinvestigated the effect of high-water pressure with the co-operation of Sir Charles Parsons, who has constructed a most powerful press, by means of which water can be compressed even to 80 per cent. of its bulk.†

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* " La Vie dans les Eaux," 1891.

† Proc. Roy. Soc., *85a*, p. 332, 1911.

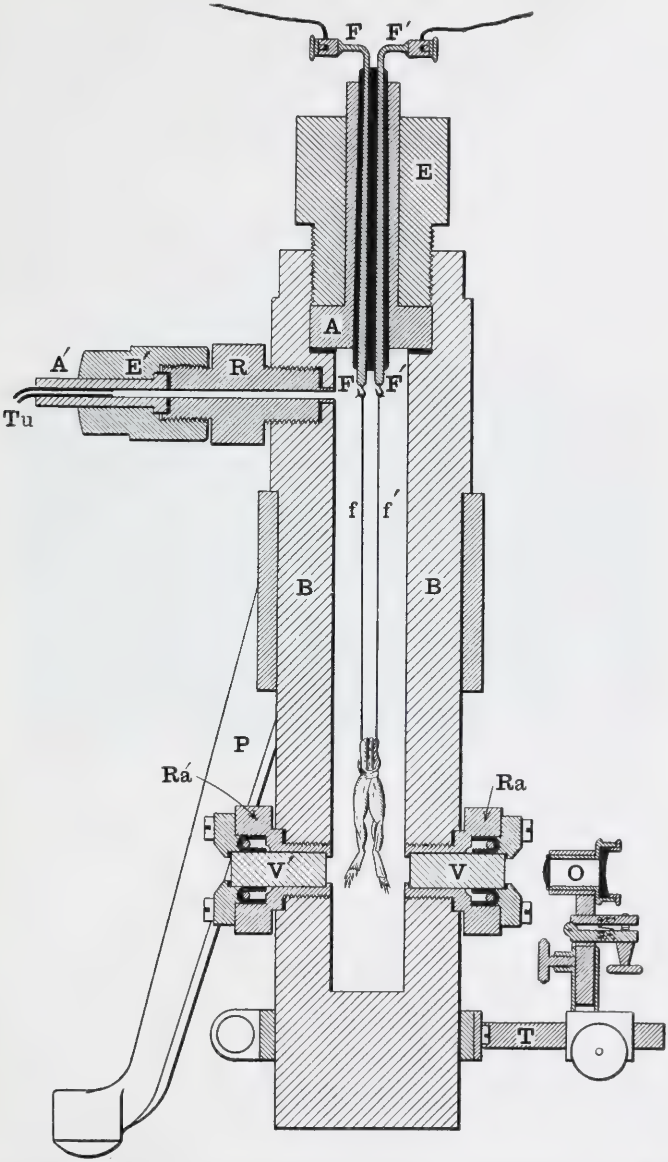

FIG. 43.—REGNARD'S APPARATUS FOR STUDYING CONTRACTION OF MUSCLE UNDER 300 TO 500 ATMOSPHERES OF WATER-PRESSURE.

Frogs with their brains destroyed preserve undiminished their reflex action and beat of heart after exposure for two hours to 300 atmospheres. Exposure to 400 atmospheres for one hour causes complete paralysis ; the muscle structure is disorganized, and the myelin changed in the nerve fibres, so that it can be squeezed out in droplets. Frog muscles exposed without the covering of skin are disorganized in shorter time. Leeches and the larvæ of gnats are rendered motionless by exposure to 500 atmospheres for one hour, but soon recover. Leeches are destroyed by exposure for one hour to 700 atmospheres, and gnats' larvæ by 800 to 900 atmospheres. Star-fish and crabs were killed by ten minutes' exposure to 500 atmospheres, while shellfish, a sea cucumber, and two sea worms survived. Coli bacilli withstood exposure to 1,750 atmospheres for ten minutes, while oysters and other shellfish were destroyed.

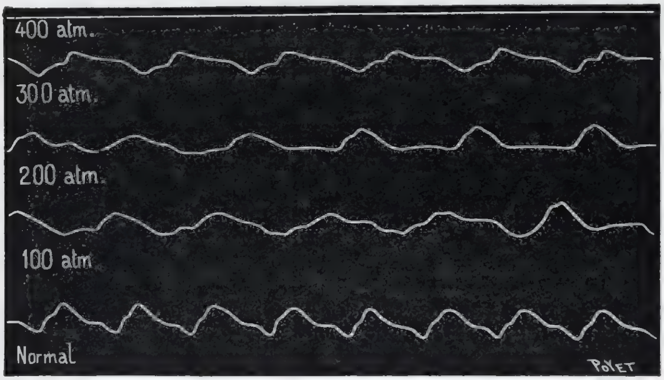

FIG. 44.—CURVES OF FROG'S HEART (REGNARD).
Contraction is good at 300, and abolished at 400 atmospheres.

It is clear, then, that while enormous pressures have no mechanical effect, the water itself becomes chemically destructive at a certain pressure. The deep sea organisms must have become evolved so as to stand a higher pressure of water than frog's muscle. The nature of the skin makes a great difference in protecting the protoplasm from the action of the water, as shown particularly by the greater tolerance of frog's muscle clothed in skin, and of the gnat's larva with a chitinous coat.

When gold-fish were suddenly compressed to 1,000 pounds pressure, they sank helpless to the bottom, owing to the compression of the air in their swim-bladder. After a short time they adjusted their specific gravity again, and began freely swimming about unconcerned by the high-water pressure.

When fish are pulled up from considerable depths, the gas in the swim-bladder expands, and they "fall" to the surface. The swim-bladder may burst or swell to a great size.

FIG. 45.—FISH BROUGHT UP FROM A CONSIDERABLE DEPTH WITH SWOLLEN SWIM-BLADDER PROJECTING FROM MOUTH (AFTER REGNARD).

CHAPTER VIII

PHYSIOLOGICAL EFFECTS OF COMPRESSED AIR

The Voice and Audition.—The voice is altered, the speech becomes nasal in quality (Triger). At +92 pounds the speech of M. Greenwood through the telephone was most unpleasantly nasal in quality, having a metallic clang, and especially when he tried talking French. The voices of the author and Greenwood lost their individual character, and seemed to sound much the same at very high pressures. The resonating effect and so the timbre of the voice is altered by the compressed (less mobile) air within the cavities of the mouth, nose, etc. Vivenot says a singer gained a semitone in compressed air. Von Schrötter, Heller, and Mager experimented with A pipes—one in the chamber at + 2·5 atmospheres, and one outside. Both were audible to the observers—to him who was inside, and to him outside. There was no difference in pitch. Greenwood and the author could find no difference in the range of audibility of a Galton whistle ; thus the hearing is not altered. There is less subjective feeling of effort in singing high tones ; whether this depends on the vocal cords or the column of air in the trachea there is no evidence to show.

According to Triger, a violin lost the volume of sound in the caisson—this, again, is probably a question of resonance. It is impossible to whistle or whisper in air at +2·5 atmospheres. The high notes can be whistled last.

There is a sensation of resistance or impediment in the resonating cavities.

Speech seems to require greater effort. It is reported that some Italians sing continuously at their work at +2 atmospheres. Von Schrötter reports that a trumpet was blown successfully at +1·3 atmospheres. No change has been observed in the larynx when examined during compression or decompression in the air-lock.

Likewise in rarefied air below 430 millimetres Hg it is not possible to whisper. Mosso says his expiration could not be made with sufficient velocity in the rarefied atmosphere.

The explanation of the failure to whisper, whistle, and the change in voice, perhaps lies in part in a change of the afferent sensations which exactly co-ordinate movement. Afferent sensations of the usual quality are not aroused by the movements of the dense air.

Sensations of pressure, deafness, and pain arise in the ear when the air is compressed. They are due to inequality between the pressure in the tympanic cavity and outside, and are at once relieved by opening the Eustachian tube. This can be done by swallowing or by forcibly expiring with the mouth shut and the nose held tight. The ear is a sensitive indicator of the change of pressure. It is " the finest indicator of the vertical movement of a balloon." Von Schrötter observed the tympanic membrane with the otoscope, and saw the light reflex alter as the pressure rose, showing the change in its shape. He also observed hyperæmia of the membrane.

There is no change in the acuteness of hearing when the pressure is equalized on either side of the membrane. Similarly, in a high balloon ascent there is no marked alteration in audition. On decompression crackling noises may be heard from the escape of air through the moist Eustachian tube. There is no resistance to the escape, the only trouble arises from difficulty in opening the tube during compression. The diminution of volume is greatest (from 1 to ½) in rising from 1 to 2 atmospheres, and the ear trouble is greatest then. Afterwards at higher pressures there is little trouble, as the volume diminishes with proportionate slowness, and enough air finds its way through the Eustachian tube when it has once been well opened.

Respiration.—Bert says " the frequency of respiration diminishes ; everyone agrees as to that." Heller, Mager, and von Schrötter found an average of two to three less per minute in twenty-seven observations at +1·7 to +2·5 atmospheres, with an increase of 3·5 per minute after " locking out," the latter change no doubt being the effect of cold. James Hunter says there is a decrease of two or three per minute ; Jaminet, Smith, and Clark have recorded an increase of frequency in compressed air. The writer has found little change, and what change there is may be attributed to rest or work in, or altered temperature of, the caisson.

Bert says it has been definitely established that the diaphragm sinks and the lungs are enlarged owing to compression of the intestinal gas, and that therefore asthmatics gain relief from exposure to compressed air.

Bert measured the increased pulmonary capacity thus: He killed a dog, and connected the trachea by one limb of a **Y**-tube to a rubber bag emptied of air. The other limb of the **Y**-tube was open. Valves were inserted in the **Y**-tube, which allowed air to enter only through the open limb, and to have its exit into the bag.

The animal was put under 3 atmospheres of pressure, and then decompressed, and the volume of air driven from the lungs into the bag measured. The volume of air in the lungs was next measured by cutting them up into bits, and squeezing the bits in a bath of water and a vessel full of water under water, and collecting the air therein. The volume of gas in the stomach and intestines was measured likewise. Example: Dog, 4·25 kilogrammes. After decompression from 3 atmospheres, there were 260 c.c. in the rubber bag. This gives 130 c.c. in the lungs at 1 atmosphere. There were only 115 c.c. in the lungs when cut up. The pulmonary capacity was therefore increased 15 c.c.

The alimentary canal yielded 60 c.c., of which 45 c.c. were in the large intestine. This would be reduced to 20 c.c. at 3 atmospheres. Of the 40 c.c. reduction in volume of abdominal contents, two-thirds is to be attributed to the sinking in of the abdominal wall, and one-third to the descent of the diaphragm. The augmentation was not proportional to the pressure, because the descent of the diaphragm is resisted more than the sinking in of the abdominal wall.

Heller, Mager, and von Schrötter could not find sure evidence by percussion of the lowering of the diaphragm, of the diminution of abdominal girth, or of a change in vital capacity. R. du Bois Reymond[*] has evidenced a greater inspiratory descent of the diaphragm in +2 atmospheres by means of the Röntgen rays. The amount of abdominal gas varies greatly in individuals, and the compression effect must be considerable in some and negligible in others.

There is some evidence[†] that the vital capacity is increased in

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[*] *Verhl. der Physiol. Gesellschaft zu Berlin*, Juli 27, 1899.

[†] "Chrabrostin-Officieler Bericht der Russischen Kriegsmarine." 1882. "Esipoff. Officieller Bericht über die Taucherschule in Kronstadt," 1897. Cit. after von Schrötter.

divers by their pursuit. This is due, no doubt, to the greater effort of breathing, which results from the placing of the exit valve in the helmet, and the high percentage of CO_2 which divers often breathe owing to defective ventilation. Both factors increase the strength of the breathing muscles. The experiments we have detailed in Chapter II. demonstrate that under conditions of rest the partial pressure of CO_2 remains constant in the alveolar air at any pressures investigated (up to 6 atmospheres absolute), and therefore the pulmonary ventilation is unchanged. At 3 atmospheres there is in the lungs three times the volume of air, measured at atmospheric pressure, which is in the lungs at 1 atmosphere; the tidal air breathed in and out at each breath, measured at atmospheric pressure, is also three times the volume breathed at 1 atmosphere. The percentage of CO_2 in the alveolar air collected at 3 atmospheres, and analyzed at atmospheric pressure, is one-third of what is found at atmospheric pressure. The volumes of air in the lung and tidal air, at 3 atmospheres pressure, and measured at 3 atmospheres, are the same as those collected at 1 atmosphere, and measured at 1 atmosphere; the partial pressure of CO_2—*i.e.*, the percentage found at 3 atmospheres—multiplied by the pressure in atmospheres, is the same as at 1 atmosphere.

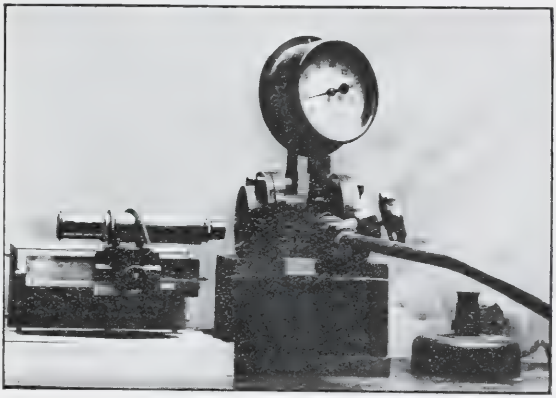

FIG. 46.—FROG CHAMBER FOR OBSERVING CIRCULATION IN FROG'S WEB AND BAT'S WING.

The *respiratory exchange* during rest, as measured by the CO_2 output in divers, is unchanged by the breathing of compressed air, as is shown by figures obtained by the Admiralty Committee.* Damant's resting output of CO_2 was the same at 210 feet as at 6 feet.

CO_2 Output during Rest, calculated from Analyses of Air in Helmet and Rate of Ventilation.

Subject.	Depth to Helmet.	Absolute Atmospheric Pressure.	CO_2 produced in Cubic Feet per Minute.
C	3	1·09	0·017 0·020
D	6	1·18	0·015 0·013
C	6	1·18	0·013 0·012
C	25	1·75	0·011
D	25	1·75	0·015
C	40	2·20	0·011 0·015
D	40	2·20	0·022 0·018
C	63	2·90	0·019 0·016
D	63	2·90	0·019 0·018
D	70	3·10	0·018
C	75	3·30	0·017
C	106	4·10	0·017
D	106	4·10	0·017
D	139	5·30	0·013
C	139	5·30	0·026
D	210	7·30	0·013

The highest figures obtained for periods of greatest exertion by analysis of air collected immediately after the work were 0·072 and 0·079 cubic feet per minute. In these experiments, under different pressures, it is not possible to compare the output for the same amount of work done, as the work varied, and the time after the work at which the sample was collected also varied.

The exposure to the highest pressures was but short, and not long enough for the high partial pressure of oxygen to exert its effect, an effect which will be studied later.

Circulation.—The caisson workers come out from the air-lock pale and sometimes slightly cyanotic, wet and chilled with the moist supersaturated air, if the lock be not properly warmed by steam coils. In the caisson and during "locking in" their faces show no sign of any circulatory effect. The lips do not

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* Report of the Admiralty Committee, pp. 17-21.

blanch, the vessels in the fundus of the eye remained unchanged, the radial pulse does not alter, the superficial veins show no sign of compression. It is amazing, then, that so many medical officers have one after the other put forth their absurd mechanical theories of compressed-air illness. M. Foley, for example: "Dès qu'on entre dans les tubes, dit-il, on est aflati." The historical account we have given of these theories shows how an ignorance of physical laws, an indifference to science and its archives, and a dogmatism which exhibits the vast difference in method between the scientific and commercial sides of medicine. The engineer and the lay public generally regard any qualified medical men as fully trained to cope with any special branch of medical science. Thus untrained men are appointed to offices which should be filled by men trained in particular, as well as general, scientific methods, and able to read the literature of other languages than their own.

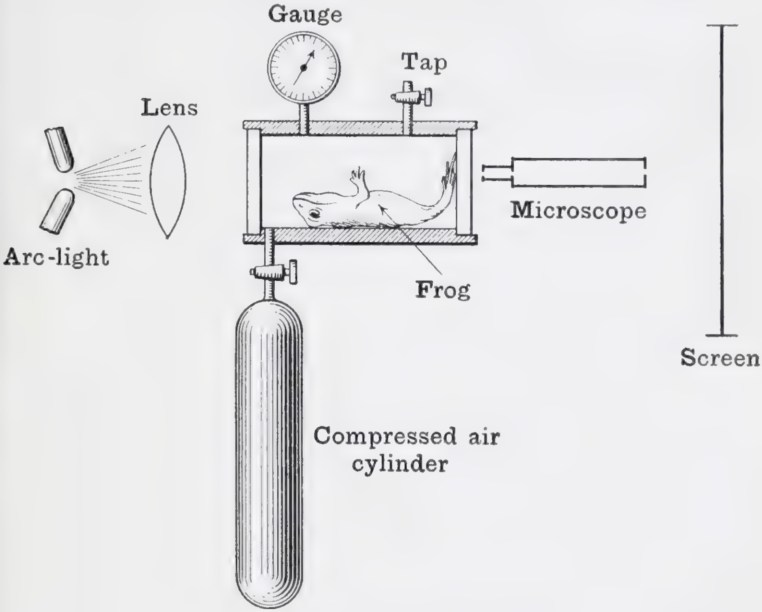

Fig. 47.—Diagram of Frog Chamber.

Bert recorded the blood pressure in two dogs by Ludwig's kymograph, and taking himself, the animal, and the apparatus into the compressed-air chamber, again recorded the blood pressure with the gauge at +530 millimetres Hg (less than 2 atmospheres absolute). His tracings show an amplification of the respiratory waves of blood pressure in the compressed air and some augmentation of pressure. The respiration was less frequent. There is nothing to show that the variations were due to the compressed air; they may have been caused by the noise of the pump, or some other source of reflex excitation. Heller, Mager, and von Schrötter compressed animals in the medical lock at the Nüssdorf Works in three to four seconds. The lock was provided with a relatively large inlet. Rabbits were trepanned and the circulation observed in the vessels of the pia mater. The circulation in the web of the frog's feet was also watched, and no change observed either while under a pressure of 2·1 atmospheres or during gradual decompression.

No change took place in the distribution of blood in the viscera of animals killed while in compressed air and then decompressed. The animals compressed in three to four seconds to 2·1 atmospheres showed no change in behaviour; the only trouble that arose was a deafness due to mechanical damage of the ear.

Knoll * in his lectures demonstrated the circulation in the web of a frog, enclosed in a chamber fitted with glass windows, and showed that rarefaction of the air had no influence on the circulation. If the foot alone was exposed to slightly rarefied air there resulted an hyperæmia, a cupping effect; the arteries, the capillaries, and veins dilated, and the rate of circulation was greatly increased. Hence the beneficial and curative effect of "cupping" painful joints, etc. Regnard found no change in the blood pressure on suddenly lowering the barometric pressure from 760 to 500.

Heller, Mager, and von Schrötter recorded the blood pressure in morphinized dogs when compressed to (and decompressed from) +4½ atmospheres. The records show that the blood pressure is independent both of the height and celerity of compression. In three out of nine experiments the pressure fell a little during the continued exposure to compressed air, and rose again on decompression. In one it rose; in the other five cases there was no effect. On rapid decompression the pressure usually rose a little, probably a reflex effect due to cooling, or to the noise of the escaping air.

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* Cit. after Heller, Mager, and von Schrötter.

The author,* at that time unwitting of the earlier experiments of Poiseuille, contrived a tubular steel pressure chamber, fitted with thick glass discs, in which he placed a curarized frog, so that the web of its foot might be illuminated with an arc light, and either observed or projected microscopically. He found that the circulation did not alter when the pressure was raised or lowered quickly +70 atmospheres. The circulation was also observed in the wing of a hibernating bat at +20 atmospheres.

The author enclosed morphinized dogs or cats in a larger chamber, having first connected the carotid artery of the animal in use with a mercurial manometer, and set the manometer recording on a clockwork drum. The manometer and drum were put with the animals inside the chamber and the lid closed. The blood pressure showed no noteworthy change on raising or lowering the pressure rapidly to 2 to 3 atmospheres.

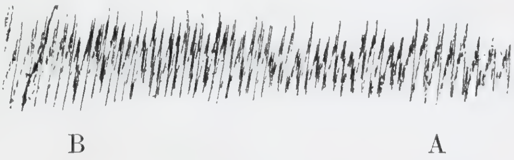

Fig. 48.—Tracing of Arterial Pressure of Dog: Pressure raised 2 Atmospheres from A to B.

In eight individuals Heller, Mager, and von Schrötter measured the blood pressure by means of von Basch's sphygmomanometer, and found in seven of them it was lowered a little in compressed air and raised on decompression. There was in most individuals also a slightly diminished frequency of breathing and pulse-rate. In some there was no noteworthy change. Most authors speak of a diminution in pulse frequency in compressed air; a few say the frequency is increased.

The average diminution found by Heller, Mager, and von Schrötter was 14·6 beats per minute in thirty-five men exposed to pressures up to +2·5 atmospheres. The frequency returns to the old rate, and generally surpasses it for a time after "locking out." There is no proportion between the diminution in frequency and the height of the barometric pressure. A rise in pressure of less than 0·5 atmosphere may lessen the frequency

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* Proceedings of the Royal Society, 1900, and vol. lxx., p. 454, 1902.

as much as a rise of 2·5 atmospheres. Similarly rarefaction of the air causes an increased frequency.

Benedict* finds breathing of 90 per cent. oxygen definitely lessens the pulse frequency in men recumbent and completely at rest.† A change from 20 to 40 per cent. of oxygen was not accompanied by any material alteration—from 20 to 60 per cent. a slight, and from 20 to 90 per cent. a positive, decrease in rate. The decrease both in oxygen and in compressed air occurs rapidly in the first few minutes.

The conditions of temperature and humidity of the air and surroundings are altered both on locking out and in, and we have no evidence as to how far these affect the pulse-rate. There is no significant change in the form of the pulse curve taken in compressed air; the amplitude may be smaller, owing probably to the damping down of the overswing of the lever in the denser medium.

In some of the men observed by Heller, Mager, and von Schrötter there was no change in the type of respiration, the form of the pulse-wave, or the blood pressure; and this being so, it is clear that the slight changes which did occur in other cases are not occasioned by the compression of the air *per se*.

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* *American Journal of Physiology*, xxviii., 1, 1911.

† W. G. Parkinson has confirmed this working with the author at the London Hospital.

CHAPTER IX

EFFECT ON RESPIRATORY EXCHANGE AND OXYGEN-POISONING

In the latter part of the eighteenth century Lavoisier and Seguin* made experiments which led them to conclude that there is no increase in the oxidative processes of the body as the result of breathing oxygen in place of air.

These observations were confirmed by Regnault and Reiset† half a century later. The uptake of O_2 was the same in 46 and 77 per cent. O_2 as in atmospheric air.

Bert, working with an apparatus modified from that of Regnault and Reiset, found—

Rat, 360 Grms.	O_2 used in 24 Hours.	CO_2 Output in 24 Hours.
At 1 atmosphere ..	12·60 l.	7·06 l.
,, 2·3 atmospheres ..	13·72	10·32
,, 4·2 ,,	11·35	6·96

On three frogs he obtained these figures reduced in each case to 20 grammes of frog weight :

	O_2 used in 5 Days.	CO_2 Output in 5 Days.
At 1·0 atmosphere ..	146 c.c.	—
,, 2·7 atmospheres ..	157 ,,	71·8
,, 4·4 ,, ..	114 ,,	62·8

According to these figures there is an optimum pressure of oxygen (40 to 50 per cent. atmospheres) above and below which the respiratory metabolism is less. These observations obviously

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* "Mém. de l'Acad. des Sciences," 1789, p. 185.

† *Ann. de Chimie et de Physique*, 1849, 3rd Series, xxvi., p. 299.

are far too few, and cannot be used justly to negative the results Regnault and Reiset obtained by very exact methods.

Later Speck,[*] improving the methods for studying the respiratory exchange in man, confirmed Regnault and Reiset's conclusion. Loewy[†] followed Speck, and by the same exact method confirmed his results.

In 1902 Rosenthal[‡] reached the opposite conclusion that much more oxygen may be absorbed and stored in the body if an increased percentage of O_2 is breathed. Durig,[§] working with the Zuntz and Loewy gas-analysis apparatus, in an exact and critical manner confirmed the earlier view that there is neither an increased consumption nor storage of oxygen on breathing oxygen-rich atmospheres. Schaternikoff[||] confirmed Durig, using an entirely different method.

J. J. R. Macleod and the author investigated the respiratory exchange of mice when exposed to an atmosphere of air or oxygen (about 95 per cent.). The mouse was placed in a glass vessel, fitted with inlet and outlet tube, and a thermometer. The outlet tubes were connected with Haldane-Pembrey tubes of (1) pumice and sulphuric acid, (2) granulated soda-lime, (3) pumice and sulphuric acid. From the increase of weight of (1) the water given off by the animal was obtained, while the increase in weight of (2) and (3) gave the output of CO_2. The O_2 intake was obtained by difference between the loss of weight of animal and gain in weight of (1), (2), and (3).

Our results show a diminution in the respiratory metabolism after exposure to oxygen for two hours, recovery taking place in air.

Mouse.	Atmosphere.	Average of CO_2 exhaled per Minute per Kilo of Body Weight.
1	Air	0·1331 gramme.
2	,,	0·1417 ,,
3	,,	0·1074 ,,
1	Oxygen	0·0831 ,,
2	,,	0·1187 ,,
3	,,	0·0993 ,,

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[*] *Arch. f. d. Ges. Physiol.*, 1879, xix., pp. 171-190.

[†] "Untersuch. über die Resp. u. Circ. bei Aenderung des Druckes u. des Sauerstoffgehaltes der Luft.," Berlin, 1895.

[‡] *Arch. f. Physiol.*, 1902, supp. bd., p. 293.

[§] *Ibid.*, 1903, supp. bd., pp. 209-369.

[||] *Ibid.*, 1904, supp. bd., pp. 135-166.

The diminution in CO_2 output was accompanied by a fall in O_2 intake and a drop in body temperature. The mice, owing to their small size, are probably more susceptible to the poisonous effect of oxygen, an effect discovered by Bert and studied by Lorrain Smith.

On investigating the cause of death of animals enclosed in a small chamber and left without ventilation, Bert found that—

At pressures inferior to 1 atmosphere animals (sparrows) live, when the exhaled CO_2 is absorbed by potash, until the partial pressure of oxygen sinks to 3·6 per cent. of an atmosphere.

In air compressed to 2 to 9 atmospheres, and superoxygenated sufficiently to prevent want of oxygen, they die when the pressure of CO_2 reaches 26 per cent. atmospheres.

In higher pressures death is caused by the pressure of oxygen, and rapidly when this attains 300 to 400 per cent. atmospheres.

In pressures of 1 to 2 atmospheres death is due partly to fall of oxygen pressure, and partly to augmentation of CO_2 pressure.

In pressures of 3 to 4 atmospheres of air the poisonous effect of the partial pressure of oxygen begins to be manifest (after long exposures). It becomes very evident in 9 to 10 atmospheres. An animal made to breathe 2, 3, or 4 atmospheres of oxygen is in the same condition as one exposed to 10, 15, or 20 atmospheres of air. Both are poisoned by the high partial pressure of oxygen.

BERT'S EXPERIMENTS ON BIRDS ENCLOSED IN SUPEROXYGENATED AIR.

Barometric Pressure.	Initial Percentage of O_2 in Chamber.	Atmospheric Pressure corresponding to O_2 Pressure in Chamber.	Duration of Life.	Duration of Life per Litre of Air at 1 Atm.	Percentage Composition of Lethal Air.		$CO_2 \times P$.
					CO_2.	O_2.	
Atm.		Atm.	Hr. Min.	Hr. Min.			
1·25	26·0	1·5	1 30	1 36	22·1	3·5	27·6
1·50	46·0	3·3	—	—	16·7	28·6	25·1
2·50	46·0	5·5	3 00	0 53	11·1	33·3	27·7
2·00	58·8	5·6	3 00	0 52	13·4	44·4	26·8
1·75	83·6	7·3	2 20	0 31	11·9	67·8	29·8
3·00	86·0	12·1	1 15	0 10	5·6	78·9	16·8
4·00	75·6	14·4*	1 00	0 7	2·1	71·1	8·4
5·00	83·0	19·7*	1 20	0 6	1·4	80·5	7·0
8·50	51·0	20·7*	0 20	0 2	0·8	47·8	6·8
5·50	85·0	22·3*	0 20	0 1	1·0	82·5	5·5

* Convulsions occurred.

BERT'S FURTHER EXPERIMENTS ON BIRDS.

Barometrical Pressure.	Pressure of O_2: Percentage of an Atmosphere.	Atmosphere of Air corresponding to Pressure of O_2.	Rectal Temperature.	Condition.
Atm.		Atm.		
1·75	150	7	—	No convulsions.
3·00	260	13	—	,,
4·00	300	15	—	Convulsions.
2·00	420	21	—	,,
5·00	420	21	32·0	Convulsions; taken out; recovered.
5·00	420	21	40·2	Convulsions; taken out at once, and recovered.
5·00	420	21	18·0	Convulsions; died in 25 minutes.

Dogs were not quite so sensitive, and exhibited convulsions strikingly at a pressure of oxygen corresponding to 19 atmospheres of air. The duration of the exposure is of importance, for convulsions may occur after some time in pressures of O_2, which correspond to little more than 10 atmospheres of air. The convulsions are like those induced by strychnine in successive tetanic spasms. The dogs may go as stiff as a piece of wood.

Bert collected the blood, and, analyzing it, found that in all cases where the animal succumbed to oxygen-poisoning, the percentage of oxygen in the blood was over 30 per cent. The solubility of oxygen in blood at body temperature from an atmosphere of oxygen is about 2·4 per cent., so that at a pressure corresponding to 4 atmospheres of O_2, or 20 atmospheres of air, there would be 9 to 10 per cent. O_2 simply dissolved in addition to the 20 per cent. combined with the hæmoglobin. The superoxygenated blood injected into another animal produced no ill-effect. It is the exposure of the central nervous system to a high partial pressure of oxygen that causes the convulsions. Normally, the tissues live almost in an anaërobic state; the oxygen dissociated from the blood is combined with the tissues, and little if any free oxygen exists. In the urine we find about 0·2 per cent.; in the intestine nil; in the saliva there may be as much as 0·5 per cent.

The respiratory metabolism was found by Bert to be notably reduced by oxygen-poisoning, and this corresponded to the marked fall in body temperature of the animals. Invertebrates, insects, spiders, worms, snails, and plants of all kinds are killed by high pressures of oxygen. "All living things," says Bert, "perish at a pressure of O_2, corresponding to 20 atmospheres of air."

Lorrain Smith has confirmed these results. Two larks at 300 per cent. atmosphere O_2 had violent convulsions in thirteen minutes. The convulsions continued at short intervals, and subsided in about one hour.

A concentration below 270 per cent. atmosphere O_2 produced no convulsions. The slow and gradual increase of O_2 tension caused congestion of the lungs, and did not excite convulsions. Lorrain Smith found that after prolonged exposure to 140 per cent. atmosphere O_2, no convulsions followed the subsequent exposure to 300 per cent. atmosphere O_2. The congestion prevents the quick rise of oxygen tension in the blood, and so the convulsions fail to appear.

Bert observed that dogs exposed to high pressure O_2 go into violent convulsions *after rapid decompression.*

For example :

1. Dog. 528 per cent. atmosphere O_2 for forty-five minutes. Decompression in 3·5 minutes. Rectal temperature, 30° C. Convulsions and death in twenty-four hours.

2. Dog. 385 per cent. atmosphere O_2 for thirty minutes. Decompression in 1·5 minutes. Rectal temperature, 36·5° C. Convulsions. Crises lasted about twenty minutes. Succeeded by muscular tremor. Recovered.

The tetanic convulsions were so intense that the dog could be held up by the foot like a piece of wood.

In only one dog out of many experiments did Bert record "s'agitant demi-convulsivement" while *under compression.* In all other cases the convulsions only came on after rapid decompression. Rapid decompression from *air*, on the other hand, did not produce convulsions, but embarrassed respiration, paralysis, or death.

It was in these dogs that Bert analyzed the blood gases, and found the convulsions became marked when the O_2 tension of the air equalled 400 per cent. atmosphere and the blood contained 30 per cent. O_2. As his animals breathed in and out of a sac of oxygen enclosed in the chamber, and the respired air contained a large excess of CO_2 (8·1 per cent. was found in one case—at 5 atmospheres this equals 40·5 per cent. atmosphere ; in another case the pressure of CO_2 was 86·2), it is impossible to draw conclusions from his analyses of the CO_2 in the blood. The animals must have been rendered comatose with CO_2. He found that blood supersaturated with O_2 up to 30 to 35 volumes per cent. had no effect when injected into dogs, and concluded that the symptoms are due not to the amount of oxygen in the blood, but to the saturation of the tissues with free oxygen. Lorrain Smith finds that the hæmoglobin can be 38 per cent. saturated with carbon monoxide by breathing air containing CO, and the O_2 displaced out of the hæmoglobin to that extent, and yet the bird be thrown into convulsions by exposure to 300 per cent. atmospheres O_2. It is therefore not the total quantity of O_2 in the blood, but *the partial pressure or concentration of* O_2 *in solution* which is the cause of the intoxication. Lorrain Smith found that convulsions were produced in mice by higher tensions of O_2 than in birds. A tension of 450 per cent. atmosphere O_2 convulsed two mice in about twenty minutes; another mouse became dyspnœic, and died without convulsions.

A rat at 268 per cent. atmosphere O_2 showed marked dyspnœa in five hours, and died overnight.

Two mice at 357 per cent. O_2 died in five hours with congested lungs.

Two mice at 230 per cent. O_2 showed great dyspnœa in nine and three-quarter hours; they recovered after decompression.

Two mice at 285 per cent. O_2 became dyspnœic in three and three-quarter hours, and one died after eight and three-quarter hours. The other recovered on decompression. In none of these animals were there convulsions.

Our numerous experiments on rats and mice confirm those of Lorrain Smith. The animals become as a rule dyspnœic, and gradually pass into coma as their CO_2 output and body temperature fall. Convulsions sometimes occur when the intoxication of the nervous system is sufficiently rapid and intense.

With 3 to 3·5 atmospheres O_2 we have not observed convulsions; with +4 to 5 atmospheres O_2 they occur, and not infrequently we have observed them in mice, rats, rabbits, and cats.

With exposure to +6 to 25 atmospheres O_2 mice and birds quickly become intensely dyspnœic and comatose, and are not convulsed.

On the other hand, exposure to 50 to 70 atmospheres O_2

instantly throws all animals into convulsions resembling those of acute asphyxia, and death rapidly follows.

Our experiments on the effect of rapid decompression from high pressures of oxygen confirm the results of Paul Bert.

The animals show a very striking tendency to strychnine-like convulsions. Sometimes there results marked reflex hyperexcitability; in other cases violent tetanic spasms occur, which may be reinvoked by handling the animals.

Bert's Experiments on Oxygen Convulsions.

Animal.	Atmosphere O_2.	Onset of Convulsions.	Onset of Coma.	Remarks.
Mouse ..	+ 3 to 3·5	none	none	Survived 6 hrs. compression.
Mouse ..	+ 4·2	12 mins.	—	Died in 2 hrs. 45 mins.
Mouse ..	+ 4 to 5	32 mins.	53 mins.	Died soon after onset of coma.
Three mice	+ 4 to 5	none	about 30 mins.	Decompressed rapidly, spasms followed.
Mouse ..	+ 5·5	5 mins.	25 mins.	Died in 35 mins.
Two mice	+ 5·5	20 mins.	—	Survived; comatose for 2 hrs.
Mouse ..	+ 10·0	none	10 mins.	Died in 45 mins.
Mouse ..	+ 25·0	none	a few mins.	Died in about 10 mins.
Linnet ..	+ 6·0	none	about 20 mins.	Rapidly decompressed. Hæmorrhages from diploë and beak.
Linnet ..	+ 9·0	none	about 20 mins.	Rapidly decompressed. Hæmorrhages from beak and in diploë.
Rat ..	+ 5·2	32 mins.	soon after convulsions	Died in 57 mins.
Rat ..	+ 5·0	none	none	Survived 2 hrs. exposure. Hyperexcitable after decompression.
Rabbit ..	+ 5·2	17 mins.	45 mins.	Died in about 60 mins.
Cat ..	+ 5·2	3 hrs. 30 mins., one fit only	soon after fit	Salivation began in 3 hrs. 12 mins. Died in 5 hrs. 20 mins.

With air pressures up to + 12 atmospheres we have not observed convulsions during compression, the process of intoxication is too gradual.

After rapid decompression animals are often thrown into convulsions owing to the frothing of gas in the heart and consequent asphyxia, or to bubbles of gas set free in the nervous system. The convulsions soon terminate in paralysis. After rapid decompression from oxygen, on the other hand, convulsions continue to be excited, for the oxygen gas set free maintains the life of the tissues.

In the case of compressed air the chief gas set free is nitrogen, and as this produces want of oxygen the convulsions quickly terminate in paralysis. The convulsions which Bert details as occurring in dogs are clearly decompression results, and due to the effervescence of oxygen gas in the central nervous system. The convulsions which occur during compression are due to the high tension of the oxygen in solution in the tissue lymph. They occur by no means constantly, but only in certain individuals and under certain conditions. Often dyspnœa, coma, and paralysis come on without any marked stage of exaltation. There is one sign of excitement which is almost always present in mice, and that is rapid cleaning movements of the face. The convulsions seem never to occur when the O_2 tension is below 300 per cent. atmospheres, or above 600 per cent. atmospheres,

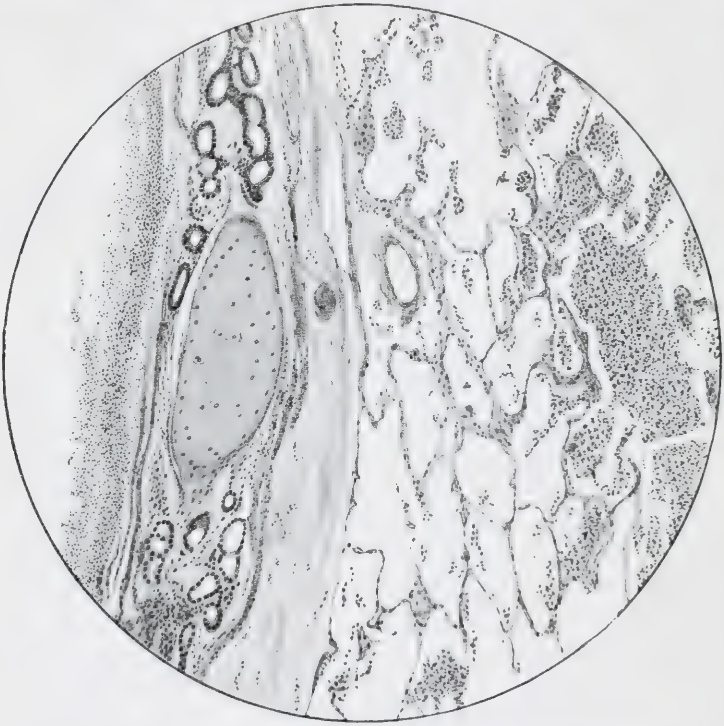

FIG. 49.—OXYGEN POISONING: EXUDATION IN BRONCHIAL TUBE AND ALVEOLI OF LUNG.

excepting the instantaneous convulsions which precede the death of animals exposed to enormous pressures such as +60 to 70 atmospheres. We may assume that with pressures below 300 per cent. atmospheres O_2, the amount of gas in solution is not sufficient to excite; that with pressures above 600 per cent. atmospheres O_2 the inflammation of the lung causes the collapse of the animal.

Lorrain Smith, while engaged in an investigation on the partial pressure of oxygen in the blood, made the striking discovery "that exposure of animals to a pressure of 170 to 180 per cent. of an atmosphere of O_2 causes, in a short time, diminution in the power of the lungs to actively absorb oxygen," and produces pneumonia. "The tissues of the lungs showed intense congestion in the large and small bloodvessels. The alveoli were to a large extent filled with an exudate, which was granular and fibrillated in appearance, but did not give the fibrin stain by

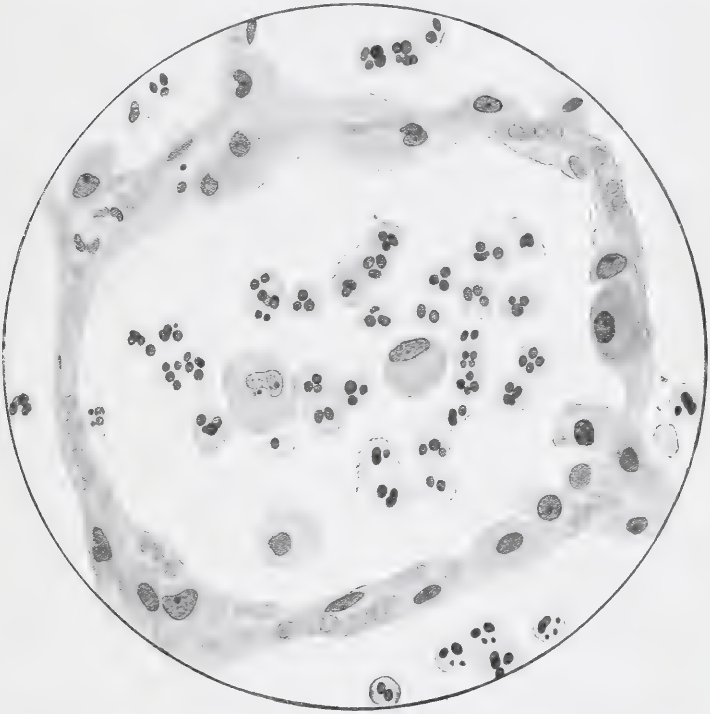

Fig. 50.—Oxygen Poisoning: Alveolus of Lung (High Power). Exudation of Leucocytes, and Congestion of Capillaries.

Weigert's method, nor with eosin." He found that exposure to a pressure of 40 per cent. of an atmosphere O_2 for eight days had no effect; 80 per cent. killed two mice in four days, which showed congestion of the lungs; while two other mice survived unharmed. An average pressure of 125·3 per cent. killed mice in an average time of sixty-four hours, 180 per cent. in twenty-four hours, and 300 per cent. produced inflammation of the lungs in five hours.

Our results confirm those of Lorrain Smith.

High partial pressure of oxygen exercises a marked irritant effect on the lungs, producing at first congestion of the alveolar capillaries, and afterwards hæmorrhagic exudation and consolidation. To the naked eye the lungs present in the early stages a suffused redness. Patches of more intense exudation occur in the apices and edges of the lungs. At a later stage the congestion passes into typical hepatization, the lungs sink in water, and are of a dark purple colour. The pneumonia is patchy if quickly, and universal if slowly, developed.

The following tables illustrate the onset of pneumonia at different pressures of oxygen and air.

OXYGEN-POISONING AND INFLAMMATION OF THE LUNGS.

INCREASED OXYGEN PRESSURES.

Animal.	Atmosphere of Pure O_2.	Time under Pressure.	Symptoms of Pneumonia.	State of Lungs.
Mouse	1	6 hours	None	Animal lived.
Mouse	3 (chamber at 30° C.)	,,	..	,,
Mouse	3 (chamber at 15° C.)	3 hours	Gasping respirations	..
Mouse	4 (chamber at room temp.)	9 hours	,,	..
Mouse	5 (chamber at 30° C.)	Died in night, probably after about 12 hrs.	..	Very congested.
Mouse	6·2 (room temp.)	Died in 2½ hours	..	Intensely pneumonic.
Rabbit	..	.. 1½ ..	,,	Pneumonic.
Rat	..	,, 1½ ,,	..	Patchy pneumonia.
Cat	,,	.. 5½ ,,	Gasping respirations and salivation	Congested all over, pneumonic patches at roots of bronchi.
Two rats	6 (room temp.)	2 hours	—	Both lungs markedly congested and upper lobe pneumonic.

INCREASED AIR PRESSURES.

Animal.	Atmosphere of Air.	Time under Pressure.	Symptoms of Pneumonia.	State of Lungs.
Mouse ..	+4 to +5	Up to 24 hrs.	None	Survived.
Mouse ..	+ 7	Died in 24 to 30 hrs.	Gasping respiration	Pneumonic.
Mouse ..	+ 9	6 hrs.	,,	Survived.
Mouse ..	+10	Died in 1½ hrs.	,,	Congestion.
Dog ..	+ 7	Exposure for 6 to 7 hrs. on three successive days	Salivation, jerky respiration	Survived.
Dog ..	+ 7	Exposure for 6 to 7 hrs. twice in two days	,,	Pneumonic.
Dog ..	+ 7 (chamber warmed)	24 hrs.	Panting respiration	Survived.
Cat and kittens	+ 7 Pressure fell to +5 during night. Chamber not ventilated during night	48 hrs. Two kittens survived, but died subsequent to decompression	Difficult breathing after 24 hrs.	Intense pneumonia.

Lorrain Smith found that 180 per cent. atmosphere O_2 killed in about twenty-four hours, while 300 per cent. O_2 produced inflammation in five hours. Our results show somewhat higher powers of resistance. Thus in Experiment 2 the mouse showed no symptoms after six hours in 300 per cent. atmosphere O_2, while in Experiment 4 the mouse survived nine hours' exposure to +400 per cent. atmosphere O_2.

Lorrain Smith suggests that inflammation of the lungs may be a cause of caisson disease as well as decompression gas embolism. We do not find any evidence in our experiments to confirm this view. The highest pressure hitherto used in caissons is +3·45 atmospheres, and the men never work for shifts longer than a few hours. It seems to require about twenty-four hours at +7 atmospheres (=168 per cent. atmospheres O_2) to produce marked symptoms of pulmonary congestion.

We observed no sign of lung trouble in a monkey which was exposed on many days to +7 atmospheres for four to five hours at a time.

To test whether the pneumonia produced by long exposure to +7 atmospheres air was due to the high partial pressure of oxygen, we subjected a group of animals to air containing only 10 per cent. of oxygen. The partial pressure of oxygen was thus 84 per cent. atmospheres in place of 168 per cent. The gas being limited in quantity, we were not able to freely ventilate the chamber. Soda-lime was placed within to absorb the CO_2, but in spite of this the CO_2 content of the chamber rose to over 1 per cent. (*i.e.*, over 8 per cent. of an atmosphere). The two cats died after thirty hours' exposure, while two out of three mice which were enclosed in a nest of cotton-wool survived. There was no trace of pneumonia in the lungs of the dead animals, and we attribute the deaths to CO_2 poisoning and cold.

J. J. R. Macleod and the author studied the effect of compressed air on the metabolism of mice, using an air-tight steel pressure chamber, fitted with thick glass discs and a pressure-gauge. This chamber we connected with a cylinder of compressed air by means of an inlet tube, while by an outlet tube we connected the chamber with a meter and a set of Haldane-Pembrey absorption tubes. By controlling the taps on the inlet and outlet tubes, we kept the pressure at the required height, and at the same time maintained a ventilation current. The animal was provided with a cotton-wool bed to lessen the loss of body heat by conduction to the metal walls of the chamber. We were only able to measure the CO_2 output, as we had no means of accurately weighing the mouse in the heavy pressure chamber.

The results showed us that prolonged exposures to +4 atmospheres and upwards diminished the CO_2 output and lowered the body temperature. Thus, at +4 atmospheres the CO_2 output fell 5 to 10 per cent., and rose again when the mouse returned to normal pressure. Two hours' exposure to + 6 atmospheres lowered the CO_2 output 30 per cent., and the body temperature 9° C.

EFFECT OF +6 ATMOSPHERES.

Time.	Pressure in Atmospheres.	CO_2 Output : Grammes per Minute per Kilogramme.	Rectal Temperature.	Temperature of Chamber.
10.49 to 11.29 a.m. ..	1	0·2287	37·5° C.	20° C.
11.29 to 1.50 p.m. ..	7	0·0622	28·2° C.	21° C.
1.50 p.m.	Decompressed in 40 minutes.			
4.12 to 4.37 p.m. ..	1	0·1476	34·0° C.	-

Eight minutes' exposure to + 7 or 8 atmospheres more than halved the CO_2 output, and lowered the rectal temperature to 23° C. Four hours later the mouse had recovered so far that its temperature was 32° C. A subsequent exposure for one hour to + 12 atmospheres falling to +6 atmospheres, lowered the CO_2 excretion 75 per cent., and the body temperature to 19° C. The mouse died and showed signs of pulmonary inflammation. Exposures for an hour to +10 to 12 atmospheres reduced the CO_2 output by two-thirds, and the rectal temperatures to 15° C. The fall of CO_2 output and of body temperature is due in part to the effect of oxygen-poisoning, and in part to the cooling of the animal brought about by the saturation with moisture and density of the compressed air, which together increase its heat-conducting capacity. It is difficult for a mouse to maintain its body heat in a current of air at 20° C., if the air is wet. In dry air it can do it quite easily. The high partial pressure of oxygen depresses the metabolism, and heat production ; the wet air conducts the body heat away, and the fur of the mouse becomes wet, and loses its heat-retaining power.* On warming the chamber up to 30° C., we found the mice resisted better the depressant effect of the high pressure.

EFFECT OF +10 ATMOSPHERES AIR. CHAMBER AT 30° C.

Time.	Pressure in Atmospheres.	CO_2 Output : Grammes per Minute per Kilogramme.	Rectal Temperature.	Remarks.
12.22 to 12.42 p.m.	1	0·283	37·5	—
12.54 to 1.29 p.m.	1	0·204	–	—
1.40 to 2.25 p.m.	10	0·202		—
2.38 to 4.13 p.m.	–	0·189	—	—
4.30 to 5.35 p.m.	–	0·186	—	Breathing jerky.
5.50 to 6 p.m. ..	Slowly decompressed to 5	0·103	—	,, ,,
6.11 to 6.26 p.m.	1	0·188	34·5	Breathing normal again.

For men a cooling effect from the wet air of the caisson comes only into play during decompression in the air-lock. The air is warmed by compression, and means have to be taken to cool it and prevent the caisson becoming overwarm.

At pressures of oxygen amounting to about 4 atmospheres, symptoms of oxygen-poisoning as a rule quickly supervene, convulsions occur, and the CO_2 output may increase at this stage only to fall again very greatly during the subsequent stage of coma.

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* The air, also, coming from a compressed air cylinder is cold, owing to its expansion.

With Lorrain Smith, we found individual mice vary in susceptibility to oxygen pressure. With some the CO_2 output was markedly depressed at +2 atmospheres O_2 in a comparatively short space of time; in others not for some hours. At the higher pressures of O_2 6 to 10 atmospheres mice may become comatose in a few minutes without passing through any convulsive stage. At very high pressures, such as 60 to 70 atmospheres, mice are thrown instantly into convulsions, and die as if suddenly asphyxiated.

The following show some of our results obtained from rats and a young rabbit:

YOUNG RABBIT.

Time.	Atmosphere O_2.	CO_2 Output per Minute: in Grms.	Remarks.
10.54 a.m.	1	0·00740	—
11.25 a.m.	+2·5 to 3	—	—
11.45 a.m.	+2·5 to 3	0·00570	—
12.50 p.m.	+2·5 to 3	0·00693	—
1.20 p.m.	+2·5 to 3	0·00637	—
2 p.m.	+2·5 to 3	0·00690	—
2.40 p.m.	+2·5 to 3	0·00475	—

After slow decompression the rabbit seemed all right. The body temperature was 36° C.

LARGE RAT, WEIGHT 225 GRAMMES.

Time.	Atmosphere O_2.	CO_2 Output per Minute: in Grms.	Remarks.
10.55 a.m.	+5	—	Room temperature, 22° C.
12 p.m.	+5	0·0062	—
12.20 p.m.	+5	0·0061	—
1 p.m.	+5	0·0000	—

On decompression, the rat was found moribund. The body temperature was 28° C. The lungs very congested.

LARGE RAT.

Time.	Atmosphere O_2.	CO_2 Output per Minute: in Grms.	Remarks.
11 a.m.	+4	—	Body temperature, 37° C.
11.10 a.m.	+4	0·0072	Room temperature, 19° C.
12.10 p.m.	+4	0·0030	—
12.20 p.m.	+4	0·0013	—

On decompression, animal found moribund. Body temperature 29° C.

LARGE RAT, WEIGHT 165 GRAMMES.

Time.	Atmosphere O_2.	CO_2 Output per Minute : in Grms.	Remarks.
10.50 a.m.	+ 2 to 3	—	Room temperature 18° C.
11.55 a.m.	+ 2 to 3	0·0087	Body temperature 37° C.
12.10 p.m.	+ 2 to 3	0·0068	—
12.45 p.m.	+ 2 to 3	0·0107	—
2.5 p.m.	+ 2 to 3	0·0079	—
2.45 p.m.	+ 2 to 3	0·0054	—

Decompressed slowly ; animal seemed all right. Body temperature, 36° C.

YOUNG RAT.

Time.	Atmosphere O_2.	CO_2 Output per Minute : in Grms.	Remarks.
10.35 a.m.	+ 3 to 4	—	Room temperature, 20° C.
10.45 a.m.	+ 3 to 4	0·0058	Body temperature, 37° C.
12.10 p.m.	+ 3 to 4	0·0035	—
12.30 p.m.	+ 3 to 4	0·0042	—
1.35 p.m.	+ 3 to 4	0·0033	—
2 p.m.	+ 3 to 4	0·0036	—
2.55 p.m.	+ 3 to 4	0·0013	—

Decompressed. Rat moribund. Body temperature, 29° C.

LARGE RAT, WEIGHT 152 GRAMMES.

Time.	Atmosphere O_2	CO_2 Output per Minute : in Grms.	Remarks.
11.10 a.m.	+ 3½	—	Body temperature, 37·4° C.
11.30 a.m.	+ 3½	0·0056	Room temperature, 18·5° C.
11.45 a.m.	+ 3½	0·0055	—
12.47 p.m.	+ 3½	0·0049	—
1.13 p.m.	+ 3½	0·0049	—
1.53 p.m.	+ 3½	0·0038	—
			—

On decompression, the rat was inert, and the rectal temperature 32·5° C. Blood collected in conical glass and quickly analyzed. Temperature of water-bath, 18·5° C.

LARGE RAT.

Time.	Atmosphere O_2.	CO_2 Output per Minute : in Grms.	Remarks.
11.25 a.m.	+ 3	—	—
1.15 p.m.	+ 3	0·0077	—
2.17 p.m.	+ 3	0·0062	—
2.24 p.m.	+ 3	0·0060	—
3.20 p.m.	+ 3	0·0054	—

Slow decompression. Rat all right. Body temperature, 36·5° C.

LARGE RAT, WEIGHT 139 GRAMMES.

Time.	Atmosphere O_2.	CO_2 Output per Minute : in Grms.	Remarks.
10.30 a.m.	+ 4	—	Room temperature, 16·5° C.

Decompressed at 12.30. Rat all right. Body temperature, 35° C.

RAT, WEIGHT 115 GRAMMES.

Time.	Atmosphere O_2.	CO_2 Output per Minute : in Grms.	Remarks.
1.20 p.m.	+ 5	—	Body temperature, 36·6° C.
1.58 p.m.	+ 5	0·0045	—
2.37 p.m.	+ 5	0·0050	—
3.10 p.m.	+ 5	0·0052	—
3.35 p.m.	+ 5	0·0047	—
3.56 p.m.	+ 5	0·0038	—

The rat on decompression seemed somewhat inert and dull. Body temperature, 30° C.

After exposure to high pressures of O_2 and rapid decompression, the animals are in a state of rigid tetanic spasm.

1. Two large toads compressed for one hour in 20 atmospheres O_2 and rapidly decompressed. The animals went into tetanic spasms, and swelled to double their size with the gas set free in their tissues. The heart was enormously distended, tense and scarlet in colour. On letting out the froth it began to beat vigorously.

2. Toad in 20 atmospheres O_2 for five minutes. Decompressed in one minute. There was some temporary paralysis of the legs and inertness. The animal soon recovered and hopped away into a corner. The same toad was placed in 20 atmospheres O_2 for thirty-five minutes. After rapid decompression it was found alive, breathing and trying to escape. In about one minute there followed tetanic spasms and rigidity of the legs. The heart was enormously distended, immobile, scarlet, and tense. On letting out the froth it began to beat. Gas bubbles were seen in the walls of the intestine, in the lymph spaces, in the anterior chamber of the eye, in the pial vessels, etc. The lungs were enormously distended. The nerves and muscles were excitable, and the muscles contracted vigorously.

3. Rat raised to 15 atmospheres O_2 in four minutes, then

rapidly decompressed. The rat violently cleaned its face, there was tremor and tendency to spasm. The animal remained dull and inert, but recovered next day.

4. Rat in 20 atmospheres O_2 for six minutes. Rapid decompression. Respiration almost failed, tendency to tetanic spasms, paralysis of hind-legs, contracted pupils ; died in eighty minutes. Bubbles were found in the liver, mesenteric vessels, numberless small ones in the mesenteric fat in the uterus and fœtal membranes (the rat was pregnant). The spleen and intestines were greatly congested. There was almost no blood in the heart. No naked-eye hæmorrhages in the central nervous system.

5. Rat to 20 atmospheres O_2 in five minutes. Decompression to 7 atmospheres in ten minutes and to 1 atmosphere rapidly. Immediate convulsions, eyeball projecting, retinal hæmorrhages seen with ophthalmoscope ; died in ten minutes. Froth in the heart, and bubbles in the intestinal vessels and walls. No naked-eye hæmorrhages in central nervous system.

6. Rat in 20 atmospheres O_2 for two minutes. Decompression in one minute. Rapidly cleaned face, dazed condition ; a touch caused a violent jump like in first stage of strychnine-poisoning. Recovered.

7. Rat in 20 atmospheres O_2 for five minutes. Rapid decompression. Lay on its side partly paralyzed. Soon recovered and moved into cage. On taking it out it struggled, and this caused a violent epileptic fit (due to displacement of gas bubbles by the struggling ?). It quickly recovered and ran into the cage.

8. Rat in 20 atmospheres O_2 for nine minutes. Rapid decompression. Collapse, paralysis, gasping respiration, and death. Bubbles everywhere in the right heart, liver, stomach, and mesenteric vessels. General emphysema of the fat and connective tissues.

9. Guinea-pig in 10 atmospheres O_2 for two minutes. Rapid decompression. The animal at first appeared dazed, but soon recovered.

10. Guinea-pig to 22 atmospheres O_2 in four minutes. Rapid decompression. Convulsions, rolling over to right, death. Froth in the heart and lungs. Some bubbles in wall of intestine. Small pin-point hæmorrhages over base of brain. A few bubbles in the larger pial vessels.

Analyzing the blood gases obtained during the convulsions, Bert found the CO_2 diminished in two observations to 14·8 per cent. and 10·5 per cent. He concluded that the oxygen had arrested the tissue metabolism. In some of the above experiments we decapitated the animals, and, collecting the blood under petroleum, measured the CO_2 in a sample by the chemical method, using Barcroft's apparatus.

We found no diminution in the percentage of CO_2 in the blood, and were thus unable to confirm Bert's results in this respect.

The diminished CO_2 output may be ascribed to the commencing inflammation of the lung, which is produced by high pressure of O_2. The metabolism of the body is depressed thereby, hence the notable fall in body temperature. The circulation is enfeebled, and thus, in spite of lessened output and production, the percentage of CO_2 in the blood remains about normal. Martin Flack and the author have found that exposure to ozone, at concentrations of a few parts per million of air, depresses the metabolism of animals, and produces inflammation of the respiratory tract. Ozone, in such concentration, produces signs of acute irritation of the respiratory tract; in us it produced sneezing, coughing, irritation of the throat and eyes, and headache.

The question of oxygen-poisoning is of great importance in particular in regard to the use of highly compressed air, oxygen breathing apparatus for rescue work, self-contained diving dresses in which oxygen is employed, and the use of oxygen breathing for washing the dissolved nitrogen out of the body during decompression. Caisson workers and divers suffer so from the perils of dissolved nitrogen that it is most unlikely they will ever go to depths where the air is compressed to such an extent that oxygen-poisoning would soon supervene—*e.g.*, +10 to 15 atmospheres. Descent to such depths, if ever attained to, would only be for a few minutes.

The limit of the safe use of oxygen in self-contained diving dresses is set by the experimental work described above.

Mr. R. H. Davis and the author have devised such a dress wherewith no pipe, pump, or life-line is used. The diver carries in place of back-weights cylinders of a mixture of air and oxygen

(50 per cent. of oxygen) compressed to 120 atmospheres. Also a box jacketed with air to prevent loss of heat, and containing cartridges of caustic soda. The granulated soda is arranged in trays, and in such a way that the air current passes over each tray. The oxygen mixture escapes through a reducing valve at a rate of 5 litres per minute, and then through an injector apparatus set on the inlet tube leading into the helmet. The force of the oxygen acting on the injector sucks the air from the helmet through the outlet pipe and soda cartridges, and so frees the air from the exhaled CO_2.

The supply lasts for an hour, and the diver, being in touch with the surface by means of a telephone cable, and unhampered by air-pipe or life-line, is able to penetrate tunnels, mines, interior of ships, etc.

The oxygen mixture is safe to breathe up to a depth of 70 to 100 feet for thirty to sixty minutes. The 50 per cent. oxygen mixture was suggested by Haldane because pure oxygen would bring about oxygen-poisoning, and a supply of air would have to be so great to insure enough oxygen that it would last but a very little time.

FIG. 50A.—SELF-CONTAINED DIVING DRESS. (SIEBE, GORMAN & CO.)

CHAPTER X

THE BODY TEMPERATURE AND VENTILATION OF CAISSONS—NITROGENOUS METABOLISM

Body temperature is increased by severe toil. Athletes, after a cup-tie football match, were found by us to have a rectal temperature of 102° to 103° F. The same temperatures were found after a half-mile race, and on one occasion, after a three-mile race, temperatures of 104°, and even 105° F., were recorded by us (Hill and Flack). In the conditions of a compressed-air caisson, where the toil is heavy and the atmosphere wet and warm, it is not surprising to find that a rise in body temperature has been recorded. This has nothing to do with the compressed air *per se*, or with increased oxidation, erroneously assumed to take place in the superoxygenated air.

The compression of the air warms the caisson and causes the air in it to be saturated with moisture. If air be 50 per cent. saturated with water vapour, it will become saturated if compressed to 2 atmospheres pressure, supposing the temperature remains the same. The compressed saturated air entering the caisson, and becoming cooled by contact with a cold soil, may become supersaturated, and a mist then forms. Such a wet mist pervaded the Thames Tunnel Works at Greenwich when I visited them in 1911. Such a mist also occurs in the air-locks during decompression when the air is cooled by expansion. The amount of water vapour which a given volume of space can hold varies with the temperature there is found in air.

The formation of the mist can be prevented by warming the caisson or by drying the air. The caissons are as a rule too warm for efficient work. The air could be dried by passing it over trays of granulated fused calcium chloride before compression. The calcium chloride can be re-fused and used over and over again. This would be an inexpensive process, as fused calcium chloride is a cheap material.

Another way of preventing or lessening mist in a small caisson would be to compress the air to a high degree in steel containers—say, to 2,000 pounds pressure, the containers being kept cool. The air delivered to the caisson from these containers will be comparatively dry, for the vapour will be condensed into water within the containers during compression, and time will not allow for the issuing air to take up water vapour and become saturated during the period of its escape from the containers into the caisson. The mist can be prevented by raising the temperature of the air above the dew-point ; but that is objectionable, for the men do not want to work in a hot atmosphere.

The body of a working man is kept at the normal temperature by the heat-losing and heat-producing mechanisms. If he is doing hard work, the heat-production is great, for the best trained man does not turn more than one-third of the energy of the food consumed into work and two-thirds into heat. An ill-trained man has no higher efficiency than a steam-engine, and turns only 10 to 15 per cent. of the food energy into mechanical work, and wastes the rest in the form of heat. The heat-losing mechanism controls the loss of heat by radiation, convection, and evaporation of water.

The subcutaneous fat and skin form a natural garment to the body of low heat conductivity. The blood, by means of the vasomotor system, is sent either in increased or lessened volume to the skin, and the latter becomes flushed in warm, and pale in cold, atmospheres. The air warmed by the body rises by convection, and the convection currents are controlled by the putting on or taking off of clothes. The air entangled in the meshes of the clothes becomes heated to body temperature and saturated with moisture. Wind drives this air away, and replaces it with a cooler, drier air. The sweat cools the body by its evaporation, every gramme of water taking up some 540 units of heat in turning into vapour.

The confined air of a caisson saturated with moisture—say, at 75° to 80° F., and ventilated by a poor current of air—diminishes the heat loss by convection and evaporation, and throws a strain on the heat-regulating mechanism of the body. The blood is sent to the skin in increased volume, and the heart beats faster, so to maintain a rapid circulation in the skin—the radiator of the body. The sweat bedews the worker, and he has to drink much to keep up the supply of water in his body, and strip off his clothes to keep from over-heating himself. All this strain on the heat-regulating mechanism lessens the efficiency of the worker, and, by fatiguing his heart, renders the decompression more risky. To get efficient work out of men exposed to warm atmospheres, every effort should be made to keep the wet-bulb temperature below 75° F. (Haldane). It does not matter what the dry-bulb temperature is, the physiological state of the man depends not on this, but on the wet bulb. It is best that the wet bulb should not rise above 70° F.—about 60° F. is the ideal for work and health. Too dry and hot an atmosphere is also bad, for the air wets itself by evaporating water from the skin and respiratory air-ways, and renders these parts dry and uncomfortable.

Our comfort and well-being depend very largely on the sensation coming from the cutaneous nerves and those of the respiratory tract. An atmosphere which is too hot and wet, or dry, modifies the blood-flow in the skin, and the flow of tissue lymph, and so alters the chemical state of the cutaneous nerves. The same holds good for the respiratory tract. If the blood is sent in increased volume to the skin in order to keep the body cool, it flows in diminished volume through the viscera, which maintain the rich nature of its quality. If the atmosphere is oppressively hot, less work is done, so less heat is produced and less food eaten. The metabolism of the body is thus reduced, and some of the more precious building-stones required out of the foodstuffs may not be obtained in due quantity, owing to the loss of appetite. Thus the immunity to bacterial disease is lowered, and the vigour of the whole body lessened. It is the duty and advantage of the caisson engineer to maintain the wet-bulb temperature as low as possible, in the face of the heat and saturation produced by the compression of the air. It is also his duty to warm the air-lock so that the expansion of the air during decompression shall not cool the body, and, by causing vaso-constriction in the skin, alter the distribution of the blood, and so prevent the proper desaturation of the tissues from the dissolved nitrogen. In the warm caisson the skin, subcutaneous fat, etc., suffused with blood, will become saturated with nitrogen; and if these parts are rendered pale and almost bloodless by the cold of the air-lock, it is clear that the desaturation cannot take place during the locking-out period.

The chemical purity of the air, so far as concerns an increase of CO_2 up to a concentration of 1 to 2 per cent. of an atmosphere, is of far less moment to the worker than excessive heat and dampness. In estimating CO_2, we must bear in mind that it is the pressure, not the percentage, which is the ruling factor. Thus 0·5 per cent. found at 3 atmospheres equals 1·5 per cent. of an atmosphere of CO_2. Such an amount deepens the breathing and throws some extra strain on the breathing mechanism, if hard toil is done. Apart from this, it has no deleterious effect.

The following experiment shows the effect of cooling a hot, moist atmosphere. The chemical state of the atmosphere, so far as concerns deficiency of oxygen and excess of CO_2, was bad, and became worse during the cooling :

A chamber holding about 3 cubic metres of air was sealed up with the subject and observer inside. The air within was heated up by an electric stove, on which a basin of water was placed to wet the air. The subject performed a measured amount of work, and the frequency of the heart-beat recorded immediately after this work, and in particular the rapidity with which the frequency diminished during the subsequent rest was taken as the measure of the strain on the subject. The subject performed the work, (1) breathing an atmosphere hot and damp, but free from CO_2 ; (2) breathing the same atmosphere in which the CO_2 was notably increased, and the oxygen diminished ; (3) the same atmosphere as in (2), only cooled about 20° F. and agitated by fans.

	During Work.		Pulse Frequency after Work.
	Wet Bulb.	Dry Bulb.	
I.	86° to 97° F.	87° to 103° F.	142 118 second minute.
II.*.. ..	87° to 101° F.	95° to 104° F.	148 144 second minute. 136 third minute.
III.†.. ..	79° F.	81·5° to 82° F.	134 110 104

A number of such experiments have been carried out by Messrs. R. A. Rowlands and H. B. Walker with the author,

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* Atmosphere contained CO_2, 5·09 per cent. ; O_2, 16·71 per cent.

† Atmosphere contained CO_2, 5·5 per cent. ; O_2, 15·57 per cent. It was cooled and circulated by fans.

and they all demonstrate the same thing. By attending to the cooling of the caissons, greater efficiency of the workmen and less caisson disease will be obtained. The actual compression of the air opposes the evaporation of water. The layer of air next a wet surface is saturated with vapour, and the vapour has to diffuse itself through the air by a kind of percolation. The density of the compressed air delays this, and the vapour particles have to jostle their way through a crowd. To evidence this, we carried out the following experiment :

A flat dish containing a weighed quantity of concentrated sulphuric acid was placed in a small pressure chamber, while a dish of water was placed in the bottom of the chamber. The amount of water vapour taken up in a given time by the acid was determined at 1 atmosphere, and then under pressure with results like the following :

Pressure : Atmospheres absorbed.	Time.	Amount of H_2O taken up by Sulphuric Acid.	Temperature of Room.
6	40 minutes.	0·0600 gramme.	8° C.
1	40 ,,	0·0920 ,,	8° C.
6 to 6·6	30 ,,	0·0500 ,,	5° C.
1	30 ,,	0·0829 ,,	5° C.

Just as in the ventilation of a diving dress to remove the exhaled CO_2, so to remove water vapour evaporated from the body by a current of dry air the ventilation volume measured at atmospheric pressure must be increased *pari passu* with the pressure. With a uniform ventilation volume, the water vapour carried per litre will fall to $\frac{1}{2}$, $\frac{1}{3}$, and $\frac{1}{4}$ as the pressure is raised to 2, 3, and 4 atmospheres ; and to keep the amount of vapour removed constant, the ventilation must be increased two, three, and four times. J. J. R. Macleod and the writer pointed this out in 1903.* The important application to the ventilation and removal of CO_2 from the diving dress was made by Haldane (Deep-Water Diving Committee of the Admiralty, 1907).

Compressed air, owing to its density, is a better conductor of heat ; so, too, is wet air ; and we have found mice exposed to compressed air at room temperatures of 17° to 20° C. become numbed by loss of body heat. In the case of the diver and caisson worker, the external cold is as a rule more than overcome

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* *Journal of Physiology*, 1903, vol. xxix., p. 507.

by the heat imparted to the air by its compression. The effect of cold water, by numbing the hands of the diver, lessens his efficiency greatly. His hands become so insensitive, the cutaneous nerves being paralyzed by cold, that he is liable to damage his hands in using tools—*e.g.*, in hammering.

Much has been made of carbon dioxide as an agent exerting an unfavourable influence upon caisson workers. E. H. Snell* lays great stress on the good results which follow free ventilation of caissons. He says: "An increase of CO_2 from 0·04 per cent. to 0·1 per cent. at 30 pounds pressure is the forerunner of much illness."

In one of the Blackwall caissons, where the pressure was 25 to 35 pounds, illnesses were occurring at the rate of seven a day. The men were working at the bottom of the caisson; the air-supply pipe opened near the roof, and the air escaped again through the roof. The supply pipe being lengthened, the illnesses at once dropped to an average of one in two days.

The following table has been compiled by Snell to illustrate the effect of increased ventilation:

CAISSON I. PRESSURE + 25 TO 35 POUNDS.

Cubic Feet of Air per Man per Hour.	Number of Days.	Cases of Illness.	Illnesses per 100 Days.
Below 4,000	13	41	315·5
4,000 to 8,000	26	78	300·0
8,000 to 12,000	10	8	80·0
Above 12,000	12	4†	33·3

In other tables Snell seeks to prove that a ventilation of over 12,000 cubic feet per man abolishes illness. He points out that candles smoke in compressed air, but cease to do so if put within a lamp chimney so as to increase the draught. As the velocity of diffusion of a gas varies inversely as the square root of the density, he attributes the smokiness of the candle to the slow diffusion of the products of combustion. He thinks the same may hold good for man. There is no evidence in favour of this view.

Snell suggests that an increase of CO_2 from 0·04 to 0·1 per cent. may actually be the cause of caisson illness, and that CO_2 may

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* E. H. Snell, "Compressed Air Illness," London, 1896.

† Only two or three men were in the caisson on the days when these illnesses occurred, and so the total volume of air supplied to the caisson was reduced—*i.e.*, the air supplied per man was high, but low per caisson.

be the gas which in particular is set free in the blood on decompression. There is no evidence that this amount has the slightest toxic effect.

At Brooklyn caisson with 0·33 per cent. CO_2 was found on analysis, which at 3 atmospheres gives 0·99 per cent. atmospheres CO_2. In the air of a diving bell at Dover the writer found 0·7 per cent. (= 2·1 per cent. atmospheres at 3 atmospheres).

We cannot suppose that a small percentage of CO_2 in the air would contribute in any way to the setting free of CO_2 bubbles on decompression. It is true that Paul Bert and ourselves found 15 per cent. CO_2 and 85 per cent. N in the air obtained from the heart of animals killed by rapid decompression. When blood is exposed to air it gives off CO_2 owing to the very low partial pressure of this gas in the atmosphere. Similarly, when nitrogen gas is set free in the heart, some CO_2 will diffuse out.

Hunter notes that the most dangerous times in the Forth Bridge caisson were (1) when soft wet silt was being removed, (2) when concreting was going on. The excessive moisture was probably the cause of the increased illness then.

Acting on Snell's observations, which stand unconfirmed by any large series of actual analyses of the tunnel air, the London County Council have insisted on the maintenance of an enormous air-supply in other Thames' tunnel works in order to maintain the CO_2 percentage at a level little above normal. Huge air compressors have been established and the ventilation maintained at a very great expense. So far as pertaining to CO_2, this expense has been needless. Major Greenwood and the writer have never observed any bad effects upon ourselves, although we have allowed the concentration of CO_2 in our experimental chamber to rise to 1·8 per cent. We disliked the noise of the air-pump when working under pressure, and, feeling perfectly comfortable without any ventilation, cut off the pump for periods of an hour or so. In addition to the type of experiment cited above, the following show the influence of increased CO_2 and diminished O_2 pressure on animals :

Effect of Increased CO_2 Tension, together with Increased Atmospheric Pressure.

a.m.
10. Cat screwed up.
10.30. $CO_2 - 4·8$ per cent. Alæ nasi working slightly. Respirations 38 to 40. Animal sleeping comfortably.
10.45. $CO_2 - 5·7$ per cent. Alæ nasi working.

a.m.

10.45. $O_2=14$ per cent. Breathing deeper. Cat awake, and apparently quite comfortable.

Pressure raised and made $=4$ atmospheres.

$CO_2=1{\cdot}5$ per cent. on analysis.

CO_2 tension $=1{\cdot}5\times 4=6$ per cent.

No difference in behaviour of cat, which soon fell asleep again. The tension of CO_2 and the symptoms of increased respiration remained the same. The pressure was again made 1 atmosphere, and the escape of the 3 atmospheres of air by removing three-quarters of the CO_2 relieved the symptoms.

11.30. $CO_2=6{\cdot}1$ per cent. Animal breathing more deeply ; alæ nasi working.

The pressure was made $=$ 4 atmospheres.

$CO_2=1{\cdot}6$ per cent. on analysis.

CO_2 tension $=1{\cdot}6\times 4=6{\cdot}2$ per cent.

The symptoms of increased pulmonary ventilation remained unchanged.

The pressure was reduced to 1 atmosphere, and the symptoms were abolished by the escape of three-quarters of the CO_2.

p.m.

12.30. $CO_2=5{\cdot}02$ per cent. Respiration deep.

$O_2=15{\cdot}2$ per cent.

12.45 Pressure made $=4$ atmospheres.

$CO_2=1{\cdot}3$ per cent. on analysis.

CO_2 tension $=1{\cdot}3\times 4=5{\cdot}2$ per cent.

The symptoms remained the same. The pressure was lowered to 1 atmosphere, and the symptoms were relieved by the escape of three-quarters of the CO_2.

2. $CO_2=10$ per cent. Respiration heaving, 40 per minute. Cat restless, and looking anxious.

Pressure made $=4$ atmospheres.

$CO_2=2{\cdot}6$ per cent. on analysis.

CO_2 tension $=2{\cdot}6\times 4=10{\cdot}4$ per cent.

No improvement in the symptoms. Pressure lowered to 1 atmosphere ; the symptoms became at once relieved by the escape of three-quarters of the CO_2.

Effect of Diminished O_2 Tension.

a.m.

10. Cat screwed up in chamber, with no ventilation and soda-lime to absorb CO_2.

11.10. $CO_2=1{\cdot}14$ per cent. Cat quite comfortable.

$O_2=10{\cdot}04$ per cent.

11.35. $CO_2=1{\cdot}8$ per cent. Jerky movement of head with each respiration.

$O_2=7{\cdot}3$ per cent. Eyes dull, no plus working of alæ nasi.

11.45. Pressure put up to $+20$ pounds ($2\frac{1}{3}$ atmospheres). The oxygen tension thus became about 35 per cent. The aspect of the cat instantly changed, the eyes became alert, and the jerky respiration ceased.

11·50. Pressure lowered again to 1 atmosphere.

p.m.

12.35. $CO_2=4{\cdot}6$ per cent. The jerky respiration is again very evident, and the animal appears inattentive to outside influences.

$O_2=8{\cdot}5$ per cent.

This condition of the animal was instantly abolished by raising the pressure to $+$ 20 pounds. In so doing, the oxygen tension was raised to about 36 per cent., while the CO_2 tension remained unchanged. The symptoms were caused by lack of oxygen, and not by CO_2, as is shown by the effect of raising the pressure, which increased the oxygen tension, but left that of the carbon dioxide unchanged.

Marked increase in the breathing of the resting animal occurs only when the CO_2 reaches 5 to 6 per cent. of an atmosphere. Oxygen pressures of less than 10 to 12 per cent. of an atmosphere alter the breathing, the respiration becomes gasping, and quite unlike the deep, heaving respiration produced by excess of CO_2. Mountain dwellers live healthy and efficient lives at altitudes where the oxygen pressure is only 14 to 15 per cent. of an atmosphere, this fact shows that the diminution of oxygen, such as occurs in ill-ventilated factories, rooms, etc., which never equals 1 per cent. of an atmosphere, is of no account.

The following type of experiment also that shows a very considerable alteration of the chemical purity of the air, so far as concerns O_2 and CO_2, is of no account beside the overpowering discomfort produced by hot, moist air: Eight students were shut up in an air-tight chamber containing about 3 centimetres of air. No ventilation was allowed. After forty-four minutes the dry bulb stood at 87° F., the wet bulb 83° F. The CO_2 had risen to 5·26 per cent.; the oxygen had fallen to 15·1 per cent. The discomfort felt was great; all were wet with sweat, and the skin of all was flushed. The talking and laughing of the occupants had gradually become less and then ceased. On putting on the electric fans and whirling the air in the chamber, the relief was immediate and very great, and this in spite of the temperature of the chamber continuing to rise. On putting off the fans the discomfort returned. The occupants cried out for the fans. No headache or after-effect followed this type of experiment. The important economic conclusion of all these observations is this: When the wet bulb is higher than 85° F. or so, a man having to do hard work is overcome in twenty to thirty minutes by irresistible lassitude and disinclination to exert himself. Training to work under such conditions, of course, makes a difference, and big works, such as the tunnels under the Alps, have been executed in spite of the high wet bulb.

Chemical purity of the air is of importance in regard to the prevention of bacterial infection. The bacteria producing colds, tuberculosis, etc., are sprayed into the air for many yards by the coughing, sneezing, and speaking of those infected. Fluegge has shown that no ordinary ventilation current can eliminate this spray. The defensive mechanisms of the body may be able to deal with a small, and be overcome by a large, invading army of bacteria. The prevalence of colds, etc., in the winter, is due largely to the air of houses, schools, and factories being confined for the sake of warmth, so that the mass influence, or dosage of infecting bacteria, taken in is greatly increased.

Close, ill-ventilated schools have a far higher percentage of illness. In one of the old wooden hulks, used as a training-ship and crowded with boys, the sickness has reached 90 per cent. per annum. Those who live an open-air life escape infection, and also increase their immunity to disease by the bracing effect of the cold. There is no proof of any organic chemical poison in the expired air. In caissons the great cause of discomfort and fatigue is the warmth and dampness of the air, and putting on an extra supply, may heat the caisson further, owing to the heating effect on the air of the compression. Cooling the caisson or in-blown air by radiators with cold water running through them, or the use of electrically driven fans placed near the workmen, would improve matters.

In the East River tunnels, McWhorter says, the amount of aqueous vapour was very high, generally to complete saturation. Occasionally this would vary for short periods, depending upon the amount of air leakage. Hygrometers left in the tunnels never registered below 90° of saturation. The temperature in the tunnels varied with the amount of air pumped in, varying with the pressure, length of tunnel, and time of year, and averaging about 75° C. "In order to maintain perfect ventilation, it is generally conceded that from 2,000 to 3,000 cubic feet of fresh air per man per hour is more than sufficient. In the East River tunnels this amount was always exceeded, as the average amount of fresh air per hour was about 231,000 cubic feet, or about 7,699 cubic feet per man per hour."

This seems a waste of energy. It would be better to spend some of the energy in cooling the caissons at least down to 70° F. wet bulb. As a working rule, the CO_2 should be kept down to about 1-1·5 per cent. of an atmosphere.

"The amount of waste matters, such as oil from compressors, or any other organic or inorganic matter that might be forced through the air feed-pipes was relatively small, as was proved by the amount of deposit on the gauze screens at the mouth of the feed-pipes."

Air driven in by machinery and through pipes generally has a slight smell, and this is particularly the case if it is warmed by passing over steam coils. The objectionable smell and flatness of what the navy terms "potted" or "tinned" air, can be removed by the use of ozone. Ozone generated in so weak a concentration that it can hardly be detected by smell, we find, is harmless, and it is a most powerful deodorant, and relies the monotonous character of "tinned" air.*

McWhorter found a maximum of 0·1 per cent. CO_2 in the air taken from behind the "shield." At 3 atmospheres pressure, this equals 0·3 per cent. of an atmosphere. "It was found that on the charts of the four tunnels, in which the daily CO_2 fluctuation and the number of cases of bends were recorded, the amount of CO_2 bore no relation to the number of cases of illness."

It is possible that, owing to the use of explosives or the boring of tunnels through certain soils, such as coal, other and poisonous gases may appear in the caissons, to prevent which extra ventilation and careful observation is required. Two most dangerous and poisonous gases which might possibly occur are carbon monoxide and hydrogen sulphide.

Dynamite, in exploding, liberates certain gases. Under the most favourable circumstances the gases liberated are CO_2, N_2, and O_2. When the dynamite is of inferior grade, or when it is damp, or for any other reason when combustion is incomplete, the gases given off include CO, NO, CH_4, H_2, and H_2S, in amounts dependent upon the amount of incomplete combustion. Thus CO may be given off in very small percentages, or in amounts as high as 36 per cent.† CO is a colourless, odourless, and combustible gas, slightly lighter than air. It combines readily with hæmoglobin, displacing the oxygen from the blood, and so producing the ill effects and death which arise from want of oxygen. Its affinity for hæmoglobin is some 150 times as great as that of oxygen; and as the partition of the hæmoglobin between the oxygen and carbon monoxide depends on the relative affinities and concentrations, it follows that in ordinary air containing roughly 21 per cent. of an atmosphere of oxygen, 0·15 per cent. of an atmosphere of CO is dangerous to breathe for long, as it will result in about half the oxygen in hæmoglobin being displaced by CO.

The presence of CO in the atmosphere is unrevealed to the senses, and loss of consciousness after slight feelings of weakness and faintness may suddenly follow, the feelings giving the sufferer no warning of his impending danger. The safety of any confined atmosphere is best tested by the taking into it of a mouse or bird. These small animals have a metabolism about twenty

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* Hill and Flack, Proc. Roy. Soc., November 7, 1911, vol. lxxxiv., B. p. 404.

† Foster and Haldane, "Investigation of Mine Air," 1905, pp. 133, 134.

times as great per minute and gramme of body weight as a man, and their frequency of respiration is much greater than that of the heart-beat in man. Their heart beats some 600 to 700 times a minute, and their body temperature is some 3° or 4° higher than man's. They are affected by a poisonous dose of CO in about one-twentieth the time in which a man is, and thus, by their illness, warn him to escape. The hæmoglobin is turned pink by CO, and on dilution of blood to 1 in 200, the change in colour is very evident if the CO blood is compared with normal blood diluted to the same amount. On spectroscopic examination, carbon monoxide hæmoglobin gives two bands—almost in the same position as the bands of oxyhæmoglobin. COHb, unlike OHb, is not reduced by the addition of ammonium sulphide, and continues to show two bands. CO in the air of a caisson can be tested for by bubbling the air through diluted blood and comparing the colour with a control tube of the same blood.

McWhorter tested the air in the East River headings immediately after blastings had taken place, and found the maximum CO never exceeded 0·045 per cent., and even this quantity was only present for a few minutes after the blasting. Haldane says : " Anything above 0·15 per cent. must be regarded as distinctly dangerous, and probably anything over 0·3 per cent. would in time produce symptoms distinctly felt on exertion." As only 0·045 per cent. was found for a few minutes, there was no danger of CO poisoning in these tunnels. The enormous ventilation used therein would be of value in keeping the CO per cent. down during blasting. Methane was never found, while nitric oxide and sulphuretted hydrogen were present only occasionally, and in most minute quantities.

" The following CO determinations are selected from the analyses made (during the year 1907) in the four tunnels. They show what small percentages really were present in those tunnels ; but in land tunnels with poor ventilation and heavy blasting, it will readily be seen, as explained later, how rapidly CO might accumulate, in percentages high enough to be of grave concern.

" 1. Dynamite, 6 pounds 7 ounces, fifteen minutes after blasting : CO = 0·01 per cent. by volume.

" 2. Very small blast, ten minutes after firing : CO = 0·0075 per cent. by volume.

"3. Dynamite, 41 pounds 13 ounces, immediately after firing: CO = 0·031 per cent. by volume.

"4. Dynamite, 45 pounds 1 ounce, immediately after firing: CO = 0·0423 per cent. by volume.

"5. Second sample same as No. 4, but one minute after high-pressure air-line had been opened to clear heading: CO = 0·02 per cent. by volume.

"6. Sample taken ten minutes after firing of a very heavy blast, the amount of dynamite not known: first sample, CO = 0·045 per cent. by volume; second sample, CO = 0·05 per cent. by volume.

"7. Dynamite, 5 pounds 15 ounces, immediately after blasting in 'sump'—pumping chamber built in rock between tunnels—very confined: CO = 0·015 per cent. by volume.

"All these samples, with the exception of No. 7, were taken as near as possible to the 'heading' where the blasting had taken place, and represent the highest percentage of CO obtainable.

"A very fair average of the amount of CO present during the blasting period was about 0 025 per cent. by volume. This naturally varied according to the amount of dynamite used, its quality, and the completeness of its combustion. The percentage given above was not an average percentage throughout the tunnel, but that found in the heading after blasting. As these samples were taken immediately, or very shortly, after blasting, they represent the very worst atmospheric conditions. Until the 'heading' is cleared by means of either the 'blow-pipe,' a large 8 to 12-inch suction-pipe communicating with the normal air in the shaft, or the high-pressure 'air-pipe,' which clears the heading by blowing back into the tunnel all gases and smoke, the men do not resume their work. Both methods of 'clearing the heading' are very effective, for in samples, taken one hour after blasting, it was impossible to determine CO in quantities over 0·002 per cent., the minimum detectable by our method."

The practice of clearing the "heading" in poorly ventilated rock tunnels by blowing the smoke and gases back into the tunnel can hardly be recommended. In such tunnels with poor ventilation and heavy blasting, CO might easily accumulate in poisonous percentages. The remedy for CO-poisoning is inhalation of oxygen. CO may be produced by fires. Poisoning by arsenic escaping from a coke stove has been recorded.* If fires are used in caissons, the ventilation must be made adequate to blow out the products of combustion.

THE EFFECT OF COMPRESSED AIR ON THE EXCRETION OF NITROGEN HOLDING ORGANIC SUBSTANCES.

Bert compressed himself to a little less than +1 atmosphere for about three hours a day, and obtained the following results :

	Urine.	Urea.
First day. Normal pressure	1,650 l.	20·15 grm.
Second day. Compressed	2,010 ,,	24·72 ,,
Third day. Compressed	1,990 ,,	26·04 ,,
Fourth day. Compressed	2,255 ,,	21·18 ,,
Fifth day. Normal pressure	2,080 ,,	20·80 ,,
Sixth day. Normal pressure	2,150 ,,	22·50 ,,

A dog placed on a daily ration and catheterized gave—

	Urea.
First day. Normal pressure	7·9 grm.
Second day. Three atmospheres	10·4 ,,
Third day. Three atmospheres	9·0 ,,
Fourth day. Normal pressure	9·1 ,,
Fifth day. Normal pressure	8·4 ,,

From these experiments Bert concludes that moderate pressures increase the nitrogenous metabolism. Snell by observation on himself at the Blackwall Tunnel was unable to determine any effect on the urea output. In two dogs compressed to 8 atmospheres, Bert determined a considerable decrease in the urea output.

The details of Bert's experiments are as follows :

DOG.—12 kilogrammes. Fed daily at 7 a.m. on 250 grammes of bread, and 250 grammes of meat, and 500 grammes of water.

July 25.—Catheterized at 8 a.m. Experiment begins.

July 26.—Catheterized at 8 a.m. : 280 c.c. urine ; 12·1 grammes urea. Compressed to 8 atmospheres from 9 a.m. to 3 p.m. Decompressed, 3 to 5 p.m. Rectal temperature, 35·5° C. Animal appears well.

July 27.—Only half its ration eaten : 350 c.c. urine ; 3·7 grammes urea !

July 28.—No food eaten : 510 c.c. urine ; 10·3 grammes urea.

DOG.—16 kilogrammes. Same diet.

August 3.—8.30 a.m. catheterized.

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* *British Medical Journal*, December 16, 1911.

August 4.—8.30 catheterized : 475 c.c., urine ; 21·6 grammes urea. Temperature, 35·8° C. Put at 8 atmospheres from 9 a.m. to 4.50 p.m. Decompressed, 4.50 to 6.20 p.m. Temperature, 35·5° C. Animal seems well.

August 5.—245 c.c. urine ; 16·9 grammes urea.

It will be noticed that Bert only determined the urea for one day previous to compression. This is not a sufficient control. The fall from 12·1 to 3·7 grammes in the first experiment must be due to some error.

J. J. R. Macleod and the writer observed the urine of three dogs exposed to 8 atmospheres of air. The dogs (females) were prepared for catheterization. They were then placed in a metabolism cage and put on a weighed and constant diet of dog biscuit and milk—more than sufficient to supply their energy. The bladder was emptied each morning with a catheter and syringe, and the urine analyzed. After several days the animals were placed in the pressure chamber and exposed to 8 atmospheres for six to seven hours. Decompression was carried out in two hours so as to avoid all risk of air embolism, and the animals were then returned to the metabolism cage for the night. A cage was fitted up within the pressure chamber so that the urine, passed during compression, could be collected.

Experiment 1.—The dog was kept for four days at normal atmospheric pressure. On the fifth day the pressure was raised to 100 pounds to the square inch (almost +7 atmospheres), and kept at this pressure for five hours. Three hours were then taken to decompress the animal. In the urine of this day there was no definite change. During the next two days the dog was kept at normal pressure, and the urine showed a slightly increased amount of organic nitrogen. On the eighth day the dog was exposed for seven hours to 100 pounds pressure. The weather was very cold, and we tried to warm the chamber by applying a Bunsen burner to the outside. During the fourth hour the dog became restless and tore away some of the wire netting at the door of the cage. It also defæcated in the cage, and fouled its fur so that some of the urine may have been lost.

On the next day the animal was again put under 100 pounds pressure. In about the third hour it became very restless, and tore down the wire netting of the cage, and escaped into the chamber. Shortly after this the dog began to profusely salivate, while the respirations became jerky in character (oxygen-poisoning). The pupils dilated and the eyelids twitched. At the end of six hours decompression was begun. It was completed in two and a quarter hours. The dog was cold on removal, wet with saliva, and with moisture taken up from the water-saturated air of the chamber. Its respirations were jerky and somewhat embarrassed with a frequency of 62. The animal would not eat.

During the next few days the dog was kept in the metabolism cage and recovered completely.

The organic nitrogen content of the urine was distinctly increased on the ninth day when the above-described symptoms occurred. The increase persisted on the following day, and is quite remarkable, considering that the animal took no food on the tenth day, and only milk on the eleventh day. The experiment is contrary to those of Bert.

Experiment 2.—The dog died on the second day under pressure, and so rendered this experiment incomplete.

After five days' preliminary observation of the organic nitrogen output, the dog was submitted to 6 to 7 atmospheres of air from 11 a.m. to 7 p.m. The weather was cold (February). At 4 p.m. the dog commenced to salivate; there were no other symptoms. On the next day it was again placed under the same pressure. It salivated profusely and was very restless. Two hours before its removal from the cage the dog lay quiet. On removal, after slow decompression, it manifested symptoms of dyspnœa, and died twenty minutes later. Death resulted from gas embolism in spite of slow decompression, owing, we believe, to the oxygen-poisoning and pneumonia which had developed in this dog. Only 100 c.c. of urine could be obtained during the eight hours' observation of this day.

No change in the organic nitrogen output is to be detected in this animal.

Experiment 3.—The dog was exposed to + 6 to 7 atmospheres for six hours on the sixth day, and again on the twelfth and thirteenth days of observation. On the thirteenth day the dog seemed restless towards the end of the period of compression.

No noteworthy change in the urine occurred, as is shown in the table on p. 162.

The three experiments here recorded show that there is no marked and constant variation in the urinary constituents of dogs submitted to +6 to +7 atmospheres for several hours. In the case of the first dog there was, it is true, a definite increase

EXPERIMENT III.—METABOLISM.

Day.	Food.		Amount of Urine.	Specific Gravity.	Reaction.	Total Nitrogen.	Urea Nitrogen.	SO_3.	P_2O_5.	Atmosphere.
	Milk.	Biscuit.								
1	284 c.c.	one and a half	330 c.c.	1013	faintly acid	2·821	—	0·336	—	+0
2	,,	,,	330 ,,	1013	,,	2·402	1·742	0·208	—	,,
3 4	,,	,,	320 ,,	1014	,,	—	1·869	0·292	0·512	,,
5	,,	,,	265 ,,	1018	faintly alkaline	2·114	1·860	0·252	0·450	,,
6	,,	,,	250 ,,	1023	,,	3·272*	2·829	0·212	0·750	6 hrs. in +6 to +7
7	,,	,,	253 ,,	—	,,	3·080	2·535	0·253	0·483	+0
8	,,	,,	215 ,,	1018	acid	2·660	2·073	0·239	0·430	,,
9 10 11	,,	,,	163 ,,	1024	faintly acid	2·647	2·565	0·294	0·465	,,
12	,,	,,	200 ,,	1020	faintly alkaline	2·816	2·236	0·226	0·584	6 hrs. in +6 to +7
13	,,	,,	153 ,,	1022	,,	2·270	1·958	0·185	0·283	,,
14	,,	,,	208 ,,	1018	faintly acid	2·780	—	—	—	+0
15	,,	,,	225 ,,	1017	faintly alkaline	2·475	2·137	0·266	0·448	,,
16 17 18	not done	—	—	—	—	—	—	—	—	,,
19	284 c.c.	one and a half	246 c.c.	1020	faintly alkaline	2·917	2·460	0·299	0·492	+0

* Urine was cloudy and contaminated with food, so result too high.

in the output of organic nitrogen. This we are inclined to attribute to commencing oxygen-poisoning. It is evident from Experiment III. that a dog can be exposed to +6 to +7 atmospheres for six hours without alteration of its urinary constituents, and we cannot confirm Bert's two experiments conducted on dogs at the same pressure. Von Schrötter found a normal amount of urea excreted in workmen compressed to 3 atmospheres.

As to general nutrition, von Schrötter found the body weights of the men employed at the Nüssdorf Works increased somewhat, owing, no doubt, to the good hygienic conditions established there.

CHAPTER XI

THE RELATION OF AGE, BODY WEIGHT, AND FATNESS TO CAISSON ILLNESS

STATISTICS of caissons and diving works tend to suggest that the percentage number of men affected injuriously by exposure to compressed air increases with age.

Pol and Watelle record that men between eighteen and twenty-six stood the work best, and that of the 25 men dismissed for illness from the works under their inspection, 19 were over forty years old, 5 over thirty, and 1 over twenty-eight years.

Catsaras investigated 62 instances of paralysis among sponge divers, and we find that, of these, 33 were over thirty years old, 17 over twenty-five, 11 over twenty, and 1 over nineteen. These men dived about 140 feet, spent about ten minutes below, and were decompressed in about one minute.

Evidently this variation might depend on—(1) the actual age difference; (2) on an increase in mean body weight and fatness with age; (3) on a combination of (1) and (2).

A. Smith compiled the following table from the records at Brooklyn Bridge of men under forty-five years:

	Spare.	Medium	Heavy.
Lost little or no time from sickness ..	25	14	3
Taken sick	28	22	36
Paralyzed	2	3	8
Died	—	—	3

Snell gives the following table of his observations, made at the Blackwall Tunnel Works.

Unfortunately, column 2 gives not the total number employed, but only those who submitted themselves to medical inspection, which was not, at first, compulsory.

Ages.	Number of Men examined and passed.	Number of Men Taken Ill whose Ages are recorded.	Proportion of Illnesses to Every 100 Men passed.
15 to 20	55	—	—
20 ,, 25	145	15	10·3
25 ,, 30	152	37	24·3
30 ,, 35	91	19	20·9
35 ,, 40	61	14	22·9
40 ,, 45	38	10	26·3
45 ,, 50	3	5	166·0
Totals ..	545	100	

Supposing, however, that the men examined by Snell were a fair sample of the workers, they can be used as a measure of the age distribution in the whole class of employees. If there be no special liability to illness at any particular age, the number of men of a given age who suffer should be simply $n'/N \times$ total number of cases, where $N = 545$, n' the number of men within the specified age limits, as recorded above. In this way Greenwood and the writer obtained the subjoined table:

Ages.	Actual Number affected.	Theoretical Number.
15 to 20	—	10·09
20 ,, 25	15	26·61
25 ,, 30	37	27·89
30 ,, 35	19	16·70
35 ,, 40	14	11·19
40 ,, 45	10	6·97
45 ,, 50	5	0·55

In the same way, if we group the 123 cases with recorded ages given by von Schrötter from the Nüssdorf Works, and assume Snell's age distribution to hold for these works (a not very improbable assumption, since we know that many caissoniers travel from place to place through England and Europe), we have—

Ages.	Actual Number affected.	Theoretical Number.
15 to 20	1	14·43
20 ,, 25	35	38·04
25 ,, 30	43	39·88
30 ,, 35	32	23·87
35 ,, 40	19	16·00
40 ,, 45	8	9·97
45 ,, 50	5	0·79

It will be seen, therefore, that there is some evidence in favour of an age bias, but the statistics are not sufficiently detailed to give much information.

The question arises whether this is due to (1), (2), or (3). The Brooklyn results point to (2).

It is known that the velocity of the circulation and rate of respiratory exchange in small mammalia is greater than in large animals, the relatively larger surface exposure in the former necessitating a higher rate of metabolism. Since the saturation of the tissues with gas, together with its removal from them, are functions of the blood, it follows that the processes should require less time in small than large animals. If, then, we expose large and small animals to the influence of compressed air for so long a time that both will contain large quantities of dissolved gas, a decompression rate dangerous for the former should be safe for the latter.

Experiments were carried out on rats, mice, cats, rabbits, and guinea-pigs by Major Greenwood and the writer.

In all experiments the animals were exposed to a pressure of +105 pounds for periods varying from a half to two hours ; in most cases the exposure was for one hour. Decompression was effected in four and a half to seven seconds.

The tables give the gist of our results :

Rats : Weight in Grammes.	Recoveries.	Deaths.	Totals.
Below 124	28	13	41
Above 124	6	18	24
Totals	34	31	65

Animals.	Died.	Survived.	Percentage Mortality, with Probable Errors.
Young rabbits..	5	9	35·70 ± 8·640
Old rabbits	2	1	66·67 ± 18·360
Young cats	6	6	50·00 ± 9·735
Old cats	6	0	100·00 ± 8·000 (?)

The evidence in favour of the view that mice can stand rapid decompression better than rats is reasonably strong. Here body weight is apparently more important than age, full-grown mice being better subjects than young rats.

Contrasting rats and mice, we found :

	Died.	Survived.	Percentage Mortality.
Rats	6	10	37·5±8·16
Mice	3	27	10·0±3·69
Difference	—	—	27·5±8·96

Two full-grown rats (11 and 12½ ounces), and three young kittens (11, 11, 10 ounces) were exposed to +120 pounds for fifty-five minutes. Decompression time, five and a half seconds. One rat was dead on removal; two kittens and the other rat died in a few minutes; one kitten survived. The air emboli usually observed were present in all three animals.

This experiment shows little advantage on the side of the young animals.

The results we have described may be compared with the observations of earlier workers which we have collected and tabulated on p. 168. These seem to show a relative immunity of the smaller animals to rapid decompression, and a death-rate of almost 100 per cent. in the case of cats and dogs at pressures above 7 atmospheres.

The observations of J. J. R. Macleod and the writer led them to conclude that all adult dogs and cats died when decompressed in a few seconds after an hour's exposure (or more) to 8 atmospheres.

If the relative immunity of small animals be due to the greater velocity of the circulation in them, it follows that any agent which damages or slows the circulation would deprive them of their safeguard. We have tested this by exposing small animals to air pressure and then pumping chloroform into the chamber, or upsetting a bottle containing the anæsthetic placed inside.

Three young rats (4 ounces, 3 ounces, 2 ounces) and a kitten were compressed at 12.50 p.m. to +110 pounds. At 2.8 chloroform was pumped into the chamber, and at 2.11, when they were all lightly anæsthetized, decompression was effected in five and a half seconds. On opening the chamber, the kitten and one rat were found dead. The other two rats died in a few minutes. All exhibited an enormous amount of gaseous embolism except the rat which survived longest, and even in

+ Pressure in Atmospheres.	Period of Decompression.	Result.
SPARROWS (BERT):		
7	A few seconds	Death.
8 (for 5 mins.)	,,	Nil.
8 (for 2 mins.)	,,	Nil.
8 (for 2 hrs.)	,,	Death.
9½ (1 hr. 35 mins.)	,,	Nil.
10 (some minutes)	,,	Nil.
12 ,,	,,	Death.
14 ,,	,,	No immediate result; died next day.
14 ,,	,,	Death.
15 ,,	,,	Death.
MICE (PHILLIPON):		
5 (20 mins.)	1 min.	Nil.
12 (1 hr.)	1 to 2 secs.	Nil.
5 (1 hr.)	Momentary	Death.
RATS (BERT):		
5½ (1 hr. 15 mins.)	A few seconds	Nil.
6½ (1 hr. 45 mins.)	,,	Nil.
6½ (¾ hr.)	,,	Nil.
8½	2 mins.	Death (two animals).
RABBITS (BERT):		
6½ (1 hr. 45 mins.)	4½ mins.	Nil.
7 (a few minutes)	2 to 3 mins.	Nil (two animals).
8 (5 mins.)	2 to 3 ,,	Nil.
8½	2 to 3 ,,	Nil (two animals).
RABBITS (PHILLIPON):		
4 (1 hr.)	Momentary	Death.
5½ ,,	,,	Death.
5·6 ,,	,,	Death.
7 (5 mins.)	,,	Nil.
7 (1 hr.)	15 mins.	Slight symptoms; recovered.
CATS (BERT):		
8 (5 mins.)	2 to 3 mins.	Paralysis and death.
10 (9 mins.)	2 to 3 ,,	Death.
10	2 to 3 ,,	Paralysis.
DOGS (BERT):		
3½	1 to 2 mins.	Nil.
4 (15 mins.)	2 to 3 ,,	Nil.
4½	2 to 3 ,,	Nil.
5 (30 mins.)	2 to 3 ,,	Nil.
5½ (4 hrs.)	20 secs.	Nil.
6 (30 mins.)	20 ,,	Nil.
6 (2 hrs.)	20 ,,	Nil.
6 (a few minutes)	20 ,,	Slight paralysis.
6 (3½ hrs.)	20 ,,	Death.
6½ (a few minutes)	4½ mins.	Nil.
7 ,,	2 ,,	Paraplegia and death.
7 (7 mins.)	2 ,,	Paraplegia and death.
7 (10 mins.)	2½ ,,	Paralysis and death.
7½ (15 mins.)	2 ,,	Paralysis and death.
7 (a few minutes)	2¼ ,,	Paralysis and death.
7¼ ,,	1¼ ,,	Paralysis and death.
7¼ ,,	1¼ ,,	Paralysis and death.
7¼ ,,	2 ,,	Paralysis and death.
7½ ,,	2 ,,	Slight paralysis.
7½ ,,	2 ,,	Paralysis and death.
7½ ,,	2 ,,	Nil.
7¾ ,,	3 ,,	Paralysis.
8 ,,	3 to 4 ,,	Paralysis and death.
8¼ ,,	3 ,,	Paralysis and death.
8¼ ,,	3 ,,	Paralysis and death.
8½ ,,	2½ ,,	Paralysis and death.

CATSARAS' OBSERVATIONS ON DOGS.

Water Depth.	Atmospheres (Approximate).	Exposure.	Decompression Time.	Result.
Metres.			Seconds.	
34·0	+ 4½	16 mins.	40	Nil.
34·0	4½	10 ,,	50	Nil.
38·0	4¾	21 ,,	60	Nil.
40·0	5	6 ,,	60	Nil.
43·0	5⅓	4 ,,	60	Nil.
34·0	4½	2½ hrs.	40	Temporary paralysis.
36·0	4½	2 ,,	50	Temporary paralysis.
38·0	4⅔	1¾ ,,	60	Death.
40·0	5	1 ,,	60	Paralysis and death.
43·0	5⅓	1 ,,	60	Dyspnœa ; recovered.
43·7	5½	2 ,,	60	Nil.
43·7	5½	1½ ,,	60	Paralysis.
47·2	5⅔	1 ,,	50	Temporary paralysis.
53·2	6⅓	½ ,,	40	Paraplegia.
55·4	6½	25 mins.	60	Death.
60·0	7	30 ,,	60	Death.
45·0	5½	30 ,,	30	Paraplegia.

this case many emboli were seen, especially in the vena cava inferior.

Boycott and Damant found that sleepy dormice of 10 to 12 grammes can usually be killed by an exposure of one hour at +75 pounds with decompression in five seconds, while exposure to 120 pounds with the same decompression had hardly an effect on lively animals of the same weight. These experiments show that immunity depends on a rapid circulation and frequent respiration. If the dormice were in a deep sleep (hybernating, cold-blooded stage), one, and even two, hours at +75 or +90 pounds did not seem to be sufficient for them to take in enough gas to produce a fatal effect on quick decompression. Thus the hybernating dormice resembled a cold-blooded animal such as the frog.

In considering the practical bearing of these results, it is to be remembered that the conditions which enable a small animal rapidly to discharge an excess of dissolved gas also lead to its more rapid saturation. Hence, *short* exposures are relatively more dangerous for small than large animals. The advantages of small body mass and youth should accordingly be more apparent among caisson workers than in diving operations. We are not acquainted with any statistics bearing on this point.

It is interesting to note that we have no reason to think that small animals are more susceptible to oxygen-poisoning than large ones. The following observations of J. J. R. Macleod, C. Ham, and the writer are suggestive of this :

Animal.	Atmospheres of Air.	Period of Exposure.	Result.
Mouse	8	27 hrs.	Pneumonia.
Mouse	11	1½ ,,	Death.
Cat and four kittens	8 to 6	24 ,,	Pneumonia.
Dog	8	24 ,,	Gasping respirations ; recovered.
	Atmospheres of O_2 (about 90 per cent.).		
Mouse	6	2½ hrs.	Pneumonia.
Rabbit	6	1½ ,,	Pneumonia.
Rat	6	1½ ,,	Pneumonia.
Cat	6	5½ ,,	Pneumonia.
Mouse	5	12 mins.	Convulsions.
Mouse	5 to 6	32 ,,	Convulsions.
Mouse	6½	5 ,,	Convulsions.
Rat	6	32 ,,	Convulsions.
Rabbit	6	17 ,,	Convulsions.
Cat	6	3 hrs. 30 mins.	Convulsions.
Cat	4 to 5	15 mins.	Nil.
	7	3½ ,,	Convulsions.
Cat	5	3½ ,,	Convulsions.
Cat	4½	6 ,,	Convulsions.
Cat	2⅔	1 hr. 20 mins.	Convulsions.
Young rabbit .. Young mouse .. Small mouse (16 grammes) .. .. Large mouse (26 grammes) .. .. Small rat (50 grammes)	2⅔	1 hr. 40 ,,	Nil.
	4⅓	15 to 20 ,,	All the animals convulsed.

In the case of the lungs the action of the oxygen is direct, and there is no reason to suppose that the size of the animals should have any influence here. As to the convulsions, Lorrain Smith has shown that these are caused not by the amount of oxygen combined, but by the concentration of oxygen dissolved in the blood. Convulsions are as readily produced in an animal whose hæmoglobin is half saturated with carbon monoxide as in one in the normal state.

From this research we concluded that—

1. Small mammals are relatively immune from decompression effects.

2. This immunity depends on rapidity of circulation, and may be destroyed by damaging the latter with chloroform.

3. Age is probably important *per se*, but of far less importance than body weight. We have no convincing proof that two

animals of the same weight but different ages would exhibit unequal resisting powers.

4. There is no evidence that small animals are more quickly poisoned by high pressures of oxygen than large ones.

The Influence of Fatness.

From the absorption coefficients for oxygen and nitrogen given by Bohr and Bock it is calculated that 100 c.c. of water saturated with air at 15° C. absorb 0·733 c.c. of oxygen and 1·411 c.c. of nitrogen, and at 37° C. (body temperature) 0·507 c.c. O_2 and 0·975 c.c. N. Blood dissolves slightly less nitrogen than water —2·5 to 3 per cent. less.*

Vernon discovered that oil or lard has a far higher solubility. Taking a mean of all the values obtained by him, using cod-liver oil and olive oil at 15° C., the solubility of oxygen is found to be 3·1 times greater than in water, and of nitrogen 3·7 times greater. At 37° C. the solubility is practically the same, and, as it is less in the case of water, it comes out that the solubility in oil is 4·5 times greater in respect of O_2, and 5·3 greater than in water in respect of N.

Vernon's figures were for 1 atmosphere. F. J. Twort and the writer have shown that this holds good up to 7 atmospheres.

Fifty c.c. olive oil (sp. gr. 0·917) were shaken at +95 pounds for thirty-eight minutes, and allowed to stand at +95 pounds for two and a half hours. Room temperature, 17·3° C. The gases were then extracted from a sample :

	Volume of Gases (N.T.P.).	Calculated on Vernon's Results.
N	35·55	39·210
O	18·00	17·000
CO_2	1·62	1·491

Time spent in collecting sample, one minute. Pressure fell $2\frac{1}{2}$ pounds during collection. The rest of the oil was left for three days at 92 pounds, falling to 84·5 pounds. The sample gave—

	Volume of Gases (N.T.P.).	Calculated on Vernon's Results.
N	33·61	35·53
O	15·56	15·40
CO_2	1·55	1·35

The oil gave a slow evolution of visible bubbles after reduction of the pressure in ten minutes from 90 to 20 pounds, even without any oscillation of the chamber.

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* Nagel's "Handbook of Physiology," 1905, vol i., p. 62.

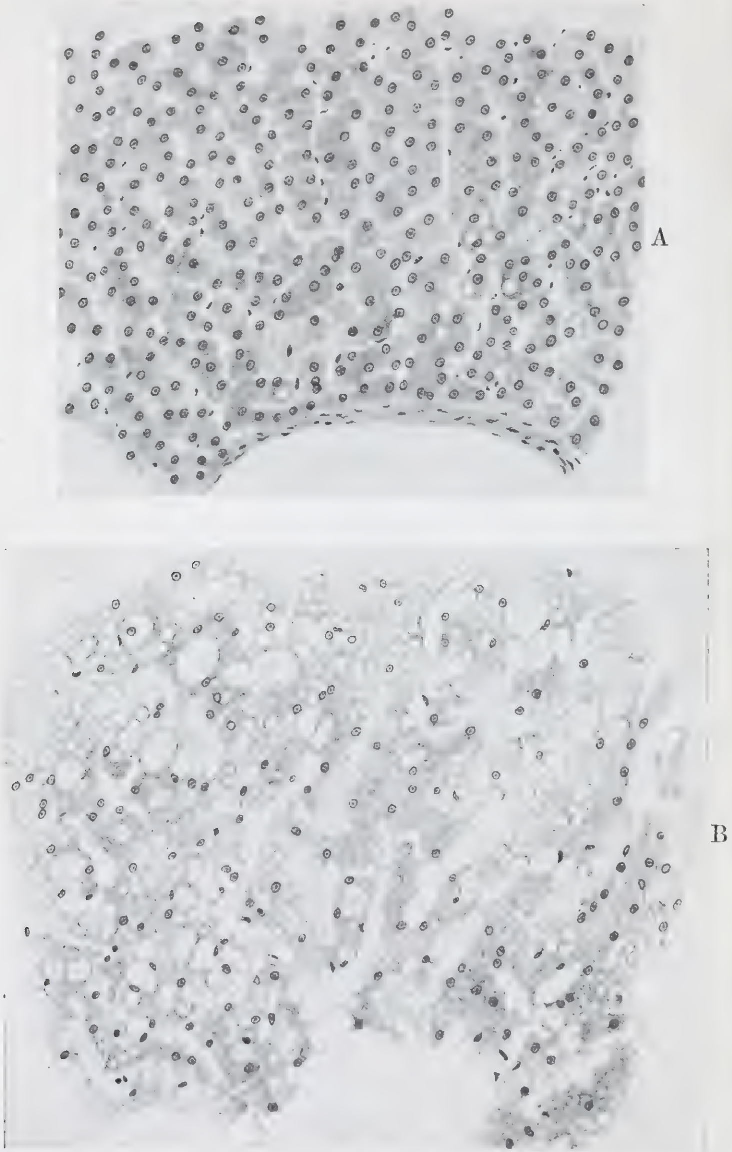

Fig. 51.—A, Normal Cat's Liver; B, Liver of Cat after Decompression from Eight Atmospheres in Five Seconds, prepared by the Same Method.

Bubbles form in the fat within the liver cells, and fill the capillaries.

Chemical analyses show that the spinal cord and peripheral nerves contain nearly 20 per cent. of fat and fat-like substances.

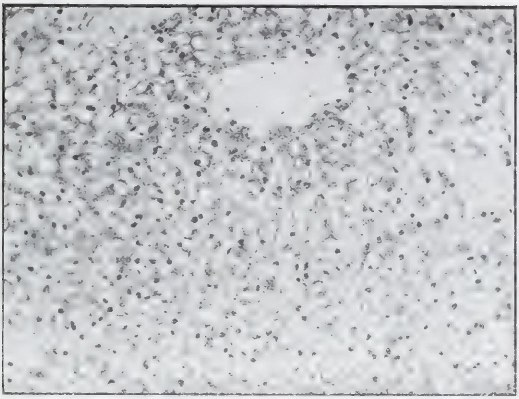

FIG. 58.—MICROPHOTOGRAPH OF THE DECOMPRESSED CAT'S LIVER (LOW POWER).

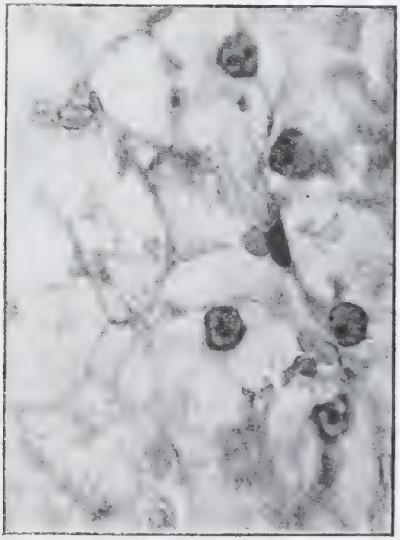

FIG. 53.—THE DECOMPRESSED CAT'S LIVER (HIGH POWER). The cells are honeycombed with bubbles.

Adipose tissue contains about 83 per cent. of fat, and yellow bone marrow no less than 96 per cent. of fat—hence the pains in the bones which afflict caisson workers. If these tissues were saturated with nitrogen at, say, 4 atmospheres, 100 c.c. of them would contain about 7 c.c. in the case of the spinal cord, and 20 c.c. in the case of yellow bone marrow, in place of about 4 c.c., in an equal volume of water. On sudden decompression, therefore, the volume of nitrogen bubbling off in a gaseous form might be two to six times as much as that from the non-fatty fluids and tissues of the body (Vernon).

"It follows that fat has an effective bulk five times greater than its actual bulk; hence the volume of the blood circulating through fat or fatty organs is relatively to the effective bulk of the tissues much reduced." Hence fat animals take longer to saturate and desaturate with nitrogen.

A. E. Boycott and G. C. C. Damant have tested the susceptibility of rats and guinea-pigs to rapid decompression, and estimated the amount of fat in the bodies of these animals by dissolving their bodies in strong caustic potash, saponifying the fat, and separating and estimating the fatty acids. Their results are grouped in seven series:

Series.	Animal.	Number.	Survived.			Died.		
			Number.	Average Weight in Grammes.	Average per Cent. Fatty Acid.	Number.	Average Weight in Grammes.	Average per Cent. Fatty Acid.
I.	Rats	54	36	136	4·5	18	129	6·0
II.	,,	29	8	69	4·2	21	85	5·5
III.	,,	40	21	130	7·0	19	112	11·7
IV.	Guinea-pigs	12	4	661	3·1	8	577	5·8
V.	,,	7	2	480	2·5	5	628	9·7
VI.	,,	40	22	548	3·7	18	589	8·8
VII.	,,	11	7	462	3·9	4	551	6·9
	Total ..	193	100	—	—	93	—	—

"All seven series give answers in the same sense, and we may conclude that we have definite experimental evidence that *fatness increases the susceptibility to death from caisson disease.* The regularity of the results in the guinea-pig experiments suggests that fatness is here the predominant influence in individual susceptibility. The difference in weight between the 'survived' and 'died' is not always in the same sense, and is in no case very large. The weight factor may therefore be relatively excluded in considering these results. Indirectly, it is of influence in that rats, like men, tend to become fatter as they grow older.* Our results show pretty clearly that females are fatter than males, and in the guinea-pig series much more susceptible. Femality, like age, is not a quality which can, *per se*, have any influence on susceptibility. The increased susceptibility of females is probably simply due to their increased fatness, which tends to further increase during pregnancy. With regard to

Fig. 54.—A, Normal Cat's Kidney; B, Kidney of Cat Decompressed from Eight Atmospheres in Five Seconds, prepared by Same Method.

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* Probably also guinea-pigs. We only have figures for six small guinea-pigs (154 to 208 grammes) which averaged 2·9 per cent. for males and 2·8 per cent. for females (Boycott & Damant).

symptoms other than death our evidence is very meagre. Some symptoms—*e.g.*, ' bends '—may be presumed to be independent of fatness.

" We do not make any suggestion that the extra gas dissolved by fat produces fatal effects by its liberation *in situ*. As far as we could make out, the immediate cause of death in these rats and guinea-pigs was the usual pulmonary air embolism. Though the fat itself usually contains many bubbles, both intravascular and among the cells, obesity doubtless favours death after long exposures, because the fat acts as a reservoir of nitrogen, and so keeps up the nitrogen pressure in the venous blood after decompression for a time sufficiently long for bubbles to form."* " If paralysis due to embolism of the spinal cord is really more frequent in fat animals—and our results are not clear on this point—we must assume a similar explanation, though it is not altogether clear that an increase in the bubbles on the venous side necessarily involves a more abundant supply of arterial emboli.†

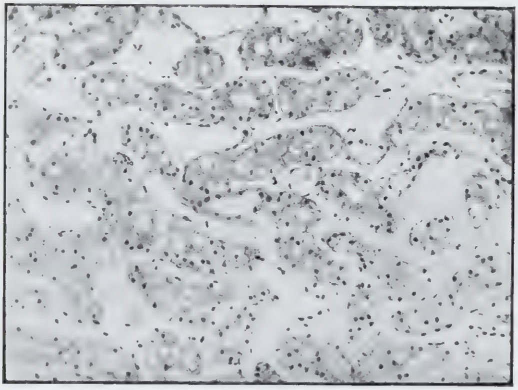

Fig. 55.—Microphotograph of the Decompressed Cat's Kidney.

" The practical conclusions are clear. Really fat men should never be allowed to work in compressed air, and plump men should be excluded from high-pressure caissons—*e.g.*, over +25 pounds—or in diving to more than about 10 fathoms, and at this depth the time of their exposure should be curtailed. If deep diving is to be undertaken, or caissons worked at pressures

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* *Journal of Hygiene*, vol. viii., p. 356.
† *Ibid.*, p. 414.

approximating to +45 pounds, skinny men should be selected. It is unfortunate that an increase of experience and skill in technical operations should so often be associated with the increase in waist measurement which accompanies the onset of middle life. Middle-aged men have a lower rate of respiratory exchange than young men. If fatness is not the explanation of this, they are at a double disadvantage, and the two factors must be multiplied rather than added together." The blood in a lean man may be more than $\frac{1}{20}$, and in the fat man as little as $\frac{1}{30}$ of the body weight. This also tells against the fat man.

The amount of fat in the lacteals, blood, and liver is increased by a fatty meal, and it seems advisable that workers in compressed air should avoid eating much fat while at work. A diet of bread and lean meat and fruit is most suitable. Indulgence in alcohol may also by a toxic effect increase the fat in the blood and liver, and so increase the risk of " bubbles."

CHAPTER XII

EFFECTS ON THE BLOOD

It is known that animals which live at high altitudes, such as the llama, have smaller and far more numerous red blood-corpuscles than animals which live on the plains. This is to increase the surface exposure of the hæmoglobin, and insure its saturation with oxygen in the lungs, and so compensate for the attenuation of the air. There is good evidence, too, that if animals are of the same litter, and some are kept on the plains, and others at lofty altitudes, that the latter after some weeks have a greater quantity of hæmoglobin in their bodies, with signs of a heightened production of red blood-corpuscles. Sea-diving birds, too, have been estimated by Bohr to have double the volume of blood which other birds have, and this explains their power to stay a minute or two under water, the extra blood allowing a greater store of oxygen to be carried. It is possible that exposure to superoxygenated or compressed air might have the opposite effect, and diminish the number of red cells and the amount of hæmoglobin, but no evidence has been brought forward in favour of this. The results obtained by H. Snell and von Schrötter show no definite change in the hæmoglobin content, specific gravity, number or morphology of the red corpuscles after three months' work in compressed-air caissons.

Effect on the Blood Gases.

Paul Bert analyzed the blood gases of dogs exposed to compressed air by drawing off samples from the carotid artery as the pressure rose—2, 3, 6, etc., atmospheres. He found that the amount of nitrogen increased, and if we take 0·97 as the coefficient of absorption of nitrogen in water at 37° C. (in blood it is a little less), the increase found by Bert corresponds to Dalton's law. All the old forms of gas-pump leak, and allow some traces of air to enter during analysis, and therefore the figures are somewhat higher than those calculated according to Dalton's law. A leak of not more than 1 per cent. of nitrogen may be taken as an average good result. Deducting this amount, the figures correspond fairly well.

TABLE OF PAUL BERT'S RESULTS AT SIMILAR PRESSURES.

O_2.	CO_2.	N_2.	Atmospheres of Air.	O_2.	CO_2.	N_2.	Atmospheres of Air.	N_2 calculated from Pressure, taking Normal at 0·97 per Cent.
18·3	37·1	2·2	1	19·1	37·7	3·0	2·00	1·94
19·4	35·3	2·2	1	20·9	35·1	4·7	3·00	2·81
18·4	47·7	2·5	1	20·0	42·2	4·4	3·00	2·81
18·3	37·1	2·2	1	20·6	40·5	6·4	5·00	4·85
22·8	50·1	2·3	1	23·9	35·2	6·0	5·00	4·85
20·2	37·1	1·8	1	23·7	35·5	6·7	5·50	5·33
19·4	35·3	2·2	1	23·7	35·6	8·1	6·00	5·87
18·4	47·7	2·5	1	21·0	41·3	7·1	6·75	6·54
18·3	37·1	2·2	1	21·1	36·8	—	7·50	7·27
22·8	50·1	2·3	1	25·4	37·6	9·5	8·00	7·76

This subject was reinvestigated by J. J. R. Macleod and the writer. The animals used for this investigation were eight dogs and two cats. They were anæsthetized with ether and chloroform, and received an injection of morphia.

A large pressure chamber was placed at our use by Messrs. Siebe and Gorman, who, by their unequalled experience in submarine engineering, were able to afford us most valuable help. The chamber was supplied with a glass window, lit with electric light, and connected with an air-pump driven by a gas engine. By means of this pump we were able to raise the pressure to + 7 atmospheres in forty-five minutes. The chamber was provided with a large exit tube, and another of the size of a pinhole. By the large tube the chamber could be decompressed in thirty to sixty seconds, by the small tube in two hours. By a third tube the chamber could be connected with a large cylinder of compressed oxygen. The cylinder contained sufficient oxygen to raise the chamber to $+6\frac{1}{3}$ atmospheres. A fourth tube was connected with the cannula placed in the carotid artery of the animal. All these tubes were provided with air-tight taps.

The blood samples were collected by connecting the fourth tube with the evacuated blood receiver. The pressure in the chamber expelled the blood and overcame any difficulty due to

TABLE OF BLOOD-GAS EXPERIMENTS.

Number of Experiment.	Animal.	Atmosphere and Pressure.	Time in Atmosphere.	Percentage of Hæmoglobin.	O_2 calculated as being absorbed by Hb in Vols. per Cent.	Percentage Amount of Gases found.			Amount of Gas dissolved in Plasma.			Remarks.
						CO_2.	O_2.	N_2.	1. By Calculation from Pressure.		2. Found by Analysis O_2.[1]	
									O_2.	N_2.		[1] For N_2 see column 7.
		1	2	3	4	5	6	7	8	9	10	
1	Dog	Air, 0 lbs.	—	95	19·0[2]	32·79	22·55	2·03	0·25	0·97	3·55	[2] Assuming that in dog's blood 100 per cent. Hb=20 vols. per cent. of O_2.
	..	Air, 100 lbs.[3] ..	30 mins.	95	19·0	37·28	22·10	8·41	1·75	7·40	3·50	
	..	Air, 100 lbs.[3] ..	2 h. 45 m.	105	21·0	40·66	25·81	11·61	1·75	7·40	4·81	[3] Decompressed between these periods.
2	Dog	Air, 0 lbs.	—	88	—	—	—	—	—	—	—	
	..	Air, 80 lbs... ..	45 mins.	88	17·8	37·70	14·74	7·48	1·25	6·75	nil	
	..	Air, 100 lbs. ..	1 hour	90	18·0	39·24	16·55	9·27	1·75	7·40	nil	
3	Cat	Air, 0 lbs.	—	70	74·0	43·40	14·20	2·00	0·25	0·97	0·20	
	,,	Air, 100 lbs. ..	1 hour	70	74·0	45·70	14·30	10·14	1·75	7·40	0·30	
	,,	Air, 100 lbs. ..	1 h. 30 m.	65	13·0	39·41	10·56	12·90[4]	1·75	7·40	nil	[4] Not corrected to N.T.P.
4	Dog	Air, 0 lbs.	—	110	22·0	36·63	16·31	2·16	0·25	0·97	nil	
	,,	Air, 100 lbs. ..	1 hour	110	—	—	—	10·19	—	7·40	—	
	,,	Air, 0 lbs.[5].. ..	—	110	22·0	37·26	20·27	2·60	0·25	0·97	nil	[5] Sample taken 35 mins. after decompression.

5	Dog	Air, 0 lbs.	—	80	16·0	35·00	14·50	1·46	—	—	—
	,,	Air, 100 to 10 lbs.[6]	—	80	16·0	39·47	13·27	2·29	—	—	—
	,,	Air, 45 lbs. to zero[7]	—	80	16·0	33·60	11·12	2·82	—	—	—
	,,	Air, 80 lbs. to zero[8]	—	80	16·0	40·70	13·70	2·86	—	—	—
6	Dog	Air, 0 lbs.	—	68 to 70	14·0	38·16	16·36	2·72	0·25	0·97[9]	2·36
	,,	Oxygen, 30 lbs. ..	15 mins.	62 to 64	12·5	40·00	17·48	1·67	2·75[10]	0·97	2·33
	,,	Oxygen, 24 to 30 lbs.	2 h. 10 m.	62	12·2	35·79	19·70	2·51	2·75	0·97	7·50
	,,	Oxygen, 30 lbs. ..	3 h. 30 m.	62	12·2	29·91	15·98	2·50	2·75	0·97	3·78
7	Dog	Air, 0 lbs.	—	95	19·0	43·30	20·64	1·84	0·25	0·97	1·64
	,,	Oxygen, 30 lbs. ..	2 hours	90	18·0	38·82	25·68	2·18	2·75	0·97	7·68
8	Dog	Air, 0 lbs.	—	90	18·0	41·84	16·40	1·97	0·25	0·97	nil
	,,	O_2, 30 lbs.	1 h. 30 m.	85	17·0	38·28	23·04	1·53	2·75	0·97	6·04
9	Dog	Air, 0 lbs.	—	94	18·8	47·00[11]	13·70	1·53	0·25	0·97	nil
	,,	Air, 100 lbs.[12] ..	1 h. 5 m.	94	18·8	40·90	17·40	11·17	1·25	7·40	nil
	,,	O_2, 95 lbs.[12] ..	40 min.	—	18·8	32·00	24·20	2·16	10·16	0·97	5·40
	,,	O_2, 90 lbs.	1 h. 35 m.	—	18·8	37·12	30·30	3·13	9·75	0·97	11·50
10	Dog	Air, 0 lbs.[13] ..	—	88	17·6	38·18	13·82	2·50	0·25	0·97	nil
	,,	Air, 46 lbs.[13] ..	30 mins.	95	19·0	35·90	10·64	5·24	1·00	4·00	nil
	,,	O_2, 46 lbs.[14] ..	30 mins.	96	19·2	43·85	22·37	4·58[15]	4·00	0·97	3·17

[6] Under 100 lbs. pressure for 2 hours; decompressed to 10 lbs. in 15 mins.

[7] Raised to 45 lbs. for 15 mins.; decompressed in 3 mins.

[8] Raised to 80 lbs., then decompressed in 1 min.

[9] A little higher, owing to about 5 per cent. N in oxygen.

[10] Assuming that 0·25 vol. per cent. O_2 is dissolved in plasma at N.T.P.

[11] Morphia injected 5 mins. before this sample was taken.

[12] Decompressed between these periods.

[13] Decompressed between these periods, and a clot removed.

[14] Meanwhile decompressed.

[15] There evidently was a slight leak of air during collection or analysis.

clotting. The gases were evacuated with the writer's gas-pump, and the Hb per cent. of the blood samples were determined by the Haldane-Gowers hæmoglobinometer.

The analyses of the gases were carried out by the potash and pyrogallic acid method, and the results reduced to 0° C. and 760 millimetres are given in the table on p. 180.

The nitrogen results obtained are again too high by 1 to 3 per cent., owing to leak during analysis ; but the results show on the whole that the arterial blood becomes saturated with nitrogen in accordance with Dalton's law. In collecting the blood at high pressure a slight leak of the compressed air into the blood receiver will naturally produce a larger error than if the leak takes place at normal pressure. Thus, 10 and 11½ volumes per cent. are found at +100 pounds in place of the calculated 7½. Experiment No. 5 shows no positive evidence of excess of nitrogen in the arterial blood, even after very rapid decompression.

The Admiralty Committee on Deep Diving report : "There is every reason to believe, although experimental evidence on the subject is not yet complete, that the blood passing through the lungs becomes instantly saturated or desaturated to the exact extent of the pressure of the nitrogen in the air breathed. Whatever, therefore, the pressure of nitrogen in the air breathed may be at a given moment, the nitrogen pressure in the arterialized blood leaving the lungs will be exactly the same. During compression, as the diver goes down, the blood leaving his lungs will always be charged with dissolved nitrogen in proportion to the absolute pressure of the air he is breathing. The same will hold good for decompression as he comes up, and since the arterial blood leaves the arteries within half a minute at most, and bubbles scarcely seem to form within this time, there will be no risk of bubbles actually forming in the *arterial* blood during decompression, except when it is almost instantaneous. With very rapid decompression, however, small bubbles which have passed through the capillaries of the lungs may easily increase in size in the arteries."

It is not denied that bubbles in plenty may be found in the arteries after rapid decompression. In particular, when the animal is distressed from pulmonary embolism, and the breathing interfered with, some of the supersaturated blood will be driven by the heart through the capillaries of the lungs into the arteries, for, owing to the interference with the breathing, the blood cannot become desaturated in the lungs.

The Saturation of the Arterial Blood and Tissues in Man.

The writer devised a method of studying the saturation and desaturation in man by means of the urinary excretion, thus avoiding the alternative and less comfortable method of drawing off samples of venous blood from the veins in the arm. Samples of arterial blood cannot, of course, be collected from man, and it is not feasible to use the chemical methods of analyzing the blood gases in 1 or 2 c.c. of blood obtained by pricking the finger. The chemical method introduced by Haldane and perfected by Barcroft is excellent so far as concerns O_2 and CO_2, which can be driven out of their chemical union with the blood by suitable reagents; but it is of no value in regard to the estimation of the nitrogen which is in solution.

If a condition of diuresis be produced by drinking considerable amounts of water, the profuse secretion of urine which results will afford some measure of the dissolved gases. The subject drinks at least a quart of warm water, and enters the chamber at such a time that he will reach the full pressure—say, +45 pounds—about thirty minutes later. The urine will be flowing freely then from the kidneys, and the bladder can be emptied every seven minutes, and samples collected. In the first series of such experiments carried out by Major Greenwood and the writer the samples of urine were run into glass bulbs with rubber connections, care being taken to expel any air bubbles and completely fill the bulbs before clamping the rubber junctions. The dissolved gas was pumped out by means of the writer's gas-pump, and analyzed by the potash and pyrogallic method.

Six analyses of normal urine were made first, and the mean of dissolved N found to be 1·14 per cent. The six results were 1·21, 1·19, 0·97, 1·10, 1·31, 1·07, 1·14 per cent., showing that the pump was giving only a small error from leaking. The larger source of error lay in the method of collecting the urine. The inclusion of any air bubble when collecting a sample of 3 or 4 atmospheres would obviously make the subsequent reading too high. The bladder was emptied, and as about 70 to 100 c.c. were excreted each time, it is clear that the urine collected in each sample was actually passed by the kidneys during each period.

The results given in the next table show that saturation of the kidney appears to be attained in about eight to ten minutes. Desaturation during uniform decompression at a rate of twenty minutes per atmosphere is, moreover, not complete. The urine after decompression was supersaturated. Of the samples passed immediately after decompression, not one yielded less than 1·64 per cent., the mean being 1·99 per cent. The fact that only traces of oxygen were found show that these results were

URINE ANALYSES FROM HILL AND GREENWOOD'S EXPERIMENTS: INDIVIDUAL OBSERVATIONS.

Pressure.	N_2 per Cent. found.	Mean.	N_2 per Cent. calculated, supposing Urine followed the Pressure.
+ o lb.	1·21, 1·19, 0·97, 1·31, 1·07	1·14	1·1*
+ 30 lbs. for less than 10 mins.	2·52, 1·67, 1·83, 2·41, 1·5	1·99	3·3
+ 30 lbs. for more than 10 mins.	3·32, 3·49, 3·29, 3·22, 3·42, 3·94 2·57	3·32	3·3
+ 45 lbs. for less than 10 mins.	2·64, 4·57 (8 mins.), 5·68 (?) (8 mins.), 4·28	4·29	4·4
+ 45 lbs. for more than 10 mins.	4·54, 3·78, 4·52 (?), 4·69, 4·35, 4·57, 3·46, 3·94	4·23	4·4
+ 30 lbs. during decompression	4·01, 3·47, 3·52, 4·25, 3·68, 3·13, 3·33	3·63	3·3
+ 15 lbs. during decompression	2·40, 2·78, 2·96, 3·16, 2·60, 3·04, 2·35, 2·73	2·75	2·2
+ 0 lb. on decompression	1·84 (4 mins.), 2·21, 1·70, 2·30, 1·64, 2·24	1·99	1·1
+ 0 lb. 15 mins. after decompression	1·34, 1·37, 2·37, 1·66, 1·45 (10 mins.)	1·64	1·1
+ 0 lb. more than 15 mins. after decompression	1·28, 1·07, 1·02	1·13	1·1

ROTHERHITHE TUNNEL WORKERS.

Source of Sample.	N_2 per Cent. found.	N_2 per Cent. calculated, supposing Urine followed the Pressure.
In tunnel (+ 17 lbs.) ..	2·38, 1·83	2·35
After decompression (decompression time, 3½ mins.)	1·60, 1·66, 1·51, 1·41, 1·75, 1·74, 1·31, 1·63	1·10

* This figure for the solubility of nitrogen is taken as approximately that found by the method employed.

not due to leak of the pump. Urine is known to contain only traces of oxygen. At the Rotherhithe Tunnel Works we gave six of the workers some beer to drink in the caisson after they had emptied the bladder, and collected their urine after decompression in three minutes from +17 pounds. The table shows the urine in these men was supersaturated. It bubbled in the collecting glass after it was passed.

The next table shows some results obtained from an Admiralty diver. The circulation through the kidneys in the state of activity produced by the drinking of water is very considerable. The weight of the two kidneys is 360 grammes, and the amount of blood flowing through them per minute is as much in diuresis. Nevertheless, with a decompression rate of twenty minutes per atmosphere equilibrium has not been established, and is not established for some ten to fifteen minutes later.

FROM ADMIRALTY DIVER C.*

Depth.	Time Below and N_2 per Cent. found.	N_2 per Cent. calculated, supposing Urine followed the Pressure.
80 feet	Below 46 mins. 20 secs. Ascended in 6 mins. 5 secs.—Sample taken 20 mins. 30 secs. after ascent: $N_2=1{\cdot}73$	1·1
84 ,,	Below 46 mins. Ascended in 5 mins.—Sample taken 11 mins. after ascent: $N_2=1{\cdot}60$	1·1
72 ,,	Below 44 mins. Ascended in 6 mins.—Sample taken 5 mins. after ascent: $N_2=2{\cdot}11$	1·1
	Sample taken 20 mins. after ascent: $N_2=1{\cdot}03$	1·1
80 ,,	Below 46 mins. Ascended in 4½ mins.—Sample taken 4 mins. after ascent: $N_2=2{\cdot}50$	1·1
	Sample taken 20½ mins. after ascent: $N_2=1{\cdot}38$	1·1

Here is a type of six further experiments carried out by J. T. Twort and H. B. Walker and the writer:

The subject was compressed to +45 pounds, and remained at that pressure for one hour. He drank a quart of water halfway through this period. Samples of urine were collected and sealed up every seven minutes, the first at +45 pounds, the remainder during decompression. The bladder was emptied each time.

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* For these samples we were indebted to Lieutenant Damant and Mr. Catto

H. B. W., twenty-four years, 10 stone—

Time.	Pressure in Pounds.	Percentage of N in Urine.	Percentage of N calculated.
4·0	+ 45	3·93	4·4
4·6 4·12	Decompressed to + 13	—	—
4·13	+ 13	3·70	2·0
4·22	+ 13	2·62	2·0
4·28	+ 13	2·30	2·0
4·34	+ 13	1·87	2·0
4·43	+ 13	1·80	2·0
4·45 4·52	Decompressed to + 0	—	—
4·55	+ 0	1·64	1·1
5·0	+ 0	1·28	1·1

It is a question whether the excess nitrogen, considering the free diuresis, does not come from the arterial blood. Can the kidney give the excess, or does the arterial blood really not get into equilibrium during its passage through the lung ? Further research must decide this question.

In our last series of experiments of this type J. F. Twort and the writer have used the modification of the Töpler gas-pump introduced by Gardner and Buckmaster. In this pump there are no taps, all the junctions are glass sealed in the flame, and the vacuum is made by pumping for two or three days before the sample is introduced, so that all the residual gas absorbed on the glass surfaces, etc., are removed. The sample is introduced into the vacuous froth chamber up a barometer tube of mercury, the open end of which is in a basin of mercury.

The samples of urine were also collected with every precaution to avoid contact with air. One end of a thin rubber sheath, wetted and collapsed so as to be empty of air, was drawn over the penis ; the other end was fastened on to a receiver full of mercury, which in its turn was connected with a reservoir of mercury which could be raised or lowered. The receiver was provided with taps. The urine was passed into rubber sheath, and then drawn into the receiver by lowering the mercury reservoir and manipulating the taps. Each receiver held 50 c.c. of urine. Normal samples from two subjects gave us 0·82 and 0·91 per cent. nitrogen. The first figure—0·82 per cent.—is lower than that usually given.* The Admiralty Committee take the

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* The solubility may vary with the concentration of salts in the urine.

figure 1 per cent. per atmosphere, and A. E. Boycott 0·9 per cent. as the amount of N dissolved per atmosphere; 0·9 is probably nearer the correct figure.

In the pressure chamber the second subject was kept at +30 pounds for fifteen minutes, then emptied his bladder, and took a sample seven minutes later while at +30 pounds. He was then lowered to +10 pounds in three minutes, and took a sample after being at +10 pounds for six minutes. He was then lowered to +0 pound in three minutes, and collected Sample III. after being at +0 pound for three minutes:

	Pressure.	Nitrogen.	Oxygen.	N. calculated on Figure 0·91.
Sample I.	+30 lbs.	3·054	0·152	2·73
,, II.	+10 ,,	2·859	0·144	1·52
,, III.	+ 0 ,,	1·609	0·081	0·91

The results show considerable supersaturation after the stage of decompression in the times given.

Our subsequent experiments were contrived to prove the efficacy of breathing oxygen as a means of expelling the nitrogen from the body and safely hastening decompression. We first investigated the effect of breathing oxygen at atmospheric pressure. The oxygen was breathed from a bag by means of a mouthpiece fitted with inspiratory and expiratory valves. The inspiration was from the bag; the expiration into the atmosphere:

Subject.	Period of Breathing O before Emptying Bladder: in Minutes.	Period of Breathing O between Emptying Bladder and Collecting Sample: in Minutes.	Nitrogen obtained.	Oxygen obtained.
1. M. F. ..	15	10	0·2576	0·1154
2. S. ..	25	10	0·3159	0·1052
3. M. F. ..	10	15	0·3206	0·0709
4. T. ..	4	7	0·3094	0·1260
		7 mins. after first sample	0·1705	0·0555
5. T. ..	10	7	0·2856	0·0587
		7 mins. after first sample	0·2392	0·0584
		7 minutes after second sample	0·4061*	0·0272

* Air breathed instead of O_2 between second and third samples.

Analyses of expired air taken just before the samples were collected gave—

	CO_2 per Cent.	Nitrogen per Cent., Approximately.	Oxygen per Cent., Approximately.
Sample I.	2·63	10	87
,, II.	2·22	10	87

The results show that by breathing oxygen we could lower easily the dissolved nitrogen to one-third or one-quarter the normal amount.

We next studied the effect of breathing oxygen at various pressures.

EXPERIMENT 1.—The subject was kept at +30 pounds for forty-four minutes, then emptied bladder, and started breathing oxygen. Took Sample I. after breathing O_2 for nine minutes; lowered to +10 pounds in two minutes. Took Sample II. after being at +10 pounds for four minutes; lowered to +0 pound in one and a half minutes. Took Sample III. after being at +0 pound for six minutes. Period between collecting Samples I. and II. was nine minutes; period between collecting Samples II. and III. was ten minutes.

	Pressure.	Nitrogen.*	Oxygen.
Sample I.	+30 lbs.	2·0910	0·2970
,, II.	+10 ,,	0·8835	0·1985
,, III.	+ 0 ,,	0·5751	0·0941

EXPERIMENT 2.—Kept at +30 pounds for fifty-one minutes, and then started breathing oxygen. Emptied bladder after breathing O_2 for five minutes. Took Sample I. seven minutes after emptying bladder; lowered to +10 pounds in one minute. Took Sample II. after being at +10 pounds for eight minutes; lowered to +0 pound, but could not obtain sufficient urine for sample. Atmosphere was very moist, as a diver was in the chamber testing a wet dress. Period between collecting Samples I. and II. was thirteen minutes.

	Pressure.	Nitrogen.*	Oxygen.
Sample I.	+30 lbs.	2·0800	0·2870
,, II.	+10 ,,	0·8913	0·1387

* Compare with nitrogen values given in the first table on page 187.

The results show that the excess of nitrogen can be cleared out of the kidneys rapidly and completely by breathing oxygen, and this would make it safe to shorten the stage of decompression very considerably. Muscular exercise ought to be taken at the same time as the oxygen is breathed in order to increase the ventilation of the lungs and the circulation some three or four times the resting value, and so wash the nitrogen out of the "slow parts."

It must be borne in mind that oxygen compressed to 2 to 3 atmospheres is a poison, and produces pneumonia and convulsions if breathed long enough. The question to settle is how long may it be breathed safely. Fleuss used his oxygen diving dress at depths of 30 feet, and stayed down breathing some 2 atmospheres of O for about half to one hour without any trouble.

Boycott and Damant tried on goats the effects of three hours' exposure to an oxygen pressure corresponding to 57 fathoms of water (362 feet, about 13 atmospheres of air or 2½ atmospheres of O_2). Out of seven animals, one died of pneumonia in the chamber, and most of the others seemed somewhat affected, though they rapidly recovered when the pressure was reduced. At an oxygen pressure corresponding to about 40 fathoms of

FIG. 56.—THE FLEUSS APPARATUS FOR USE IN MINES. (SIEBE, GORMAN AND CO.).

The subject breathes in and out of the bag through inspiratory and expiratory valves. Caustic soda is placed in the vulcanized rubber bag. The bag is protected by canvas. Oxygen enters the bag from a cylinder through a reducing valve at the rate of 1 or 2 litres a minute. A gauge shows the pressure of oxygen in the cylinder.

water ($1\frac{2}{5}$ atmospheres O_2) Haldane and Damant could not detect in themselves any symptoms either objective or subjective during short exposures.

Bornstein has breathed oxygen (90 to 95 per cent.) for forty-eight minutes (at +2 atmospheres), and two engineers at the Elbe Tunnel breathed it for thirty minutes. These important observations show the limit to which such high partial pressures of oxygen can be breathed safely by man. Bornstein has found the time limit given above must not be overstepped. He freed himself from "bends," after eight-hour exposures to +2 atmospheres, by using oxygen.

The oxygen can be breathed economically by the use of the Fleuss apparatus, which was used effectively in the great colliery disaster at Bolton (1911). This apparatus can be put on in the caisson, and oxygen breathed for ten minutes before and during decompression. This, coupled with active exercise to excite the circulation, ought to clear out the nitrogen in a very few minutes. For every atmosphere the body dissolves nitrogen to about 1 per cent. of its mass—for a 70 kilogramme man, say, 700 c.c. per atmosphere. Von Schrötter calculates that oxygen plus muscular exercise would turn out 1,000 c.c. in five minutes, probably more.

Supposing for safety's sake the oxygen is only given the diver after he has reached 30 or 40 feet from surface during stage decompression, the rate of loss of nitrogen by diffusion through the lungs will be about doubled, and the time for safe decompression for the last stages reduced to one-half.*

Oxygen is now made from liquid air, and it ought to be feasible to use it for deep work.

THE GAS SET FREE IN THE BLOOD ON RAPID DECOMPRESSION.

Bert collected and analyzed the gas set free in the right side of the heart of dogs killed by rapid decompression, and found—

	I. Per Cent.	II. Per Cent.	III. Per Cent.
CO_2	15·2	15·9	20·8
O	02·0	-	a trace
N	82·8	84·1	79·2

Von Schrötter, using the method of collection figured, found—

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* "Admiralty Committee Report," p. 55.

	I. Per Cent.	II. Per Cent.
CO_2	4·71	12·45
O	15·31	7·18
N	79·98	80·37

C. Ham and the writer placed rats in 10 to 15 or 20 atmospheres of air for a sufficient time to saturate their bodies with air at this pressure, and then decompressed them in about three seconds. The animals thus killed were sunk in a bath of strong brine, and the air in the fur and air passages disengaged. They were then cut up under a filter funnel which was closed at the top and filled with the brine. By cutting and squeezing, the gas in their bodies was disengaged and collected in the funnel. The gas was then measured and analyzed.

Fig. 57.—Gas in Heart and Coronary Vessels of Dog killed by Rapid Decompression (von Schrötter).

Taking the water in a rat's body as 66 per cent., and the coefficient of absorption of nitrogen in water exposed to air at body temperature as 1 per cent., we found the amount of this gas set free in the bodies of the rats too much. Part of the excess is due to the greater solution of N in the fat. It seemed likely, too, that the rats swallowed some air while under pressure. We therefore tied the gullet before putting the animals in the pressure chamber. Our results then corresponded better with the calculated amounts. Most of the gas was free in the peritoneal cavity. This is not the case in goats. The stomach, too, always contained large bubbles. In goats, owing to fermentation of food, and chewing the cud in the mouth, much gas often distends the stomach, and sometimes it is blown out like a drum after decompression from + 75 pounds. The following exemplify our results :

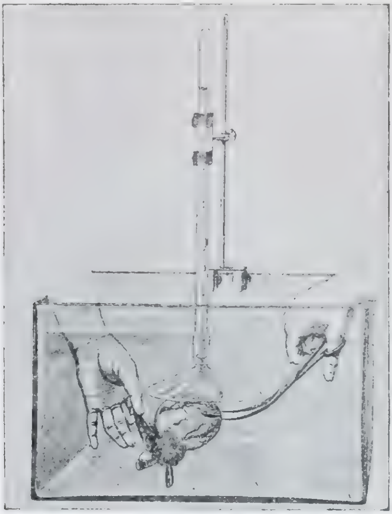

Fig. 58.—Method of Collecting Gas in Heart (von Schrötter).

Rat weighing 51 grammes, put in 16 atmospheres for two hours, gullet tied, decompressed in about three seconds—

Total gas in body	9 c.c.
CO_2	16 per cent.
O	4 ,,
N	80 ,,
Total N in body	6·95 c.c.

Rat 44 grammes at 22 atmospheres, gullet not tied—

Total gas	13·8 c.c.
CO_2	6·7 per cent.
O	8·7 ,,
N	84·6 ,,
Total N in body	11·25 c.c.

Rat 42 grammes at 22 atmospheres, gullet tied—

Total gas	10 c.c.
CO_2	10·7 per cent.
O	2·1 ,,
N	87·2 ,,
Total N in body	8 c.c.

All the results indicate that 80 to 87 per cent. of the gas set free is N. When the nitrogen is set free as bubbles, these act as a vacuum for CO_2 and O, and some of these gases are set free out of chemical combination with the blood. The oxygen is mostly used up by the tissues of the dying animal, and thus we find the chief gas besides N_2 is CO_2.

Macleod and the writer submitted frogs and toads to +20 atmospheres of oxygen for five minutes, and observed that after decompression the animals were not only convulsed, but enormously distended with gas. Mice exposed to +10 atmospheres of oxygen were not so swollen, but went into tetanic spasms. Such convulsions could be evoked by a touch, and animals killed in this state occasionally showed bubbles in the capillaries of the central nervous system. Being composed of oxygen, these emboli supplied the nerve cells with that gas until the circulation was re-established. Accordingly, the nervous inco-ordination was but temporary, and the animals in most cases recovered.

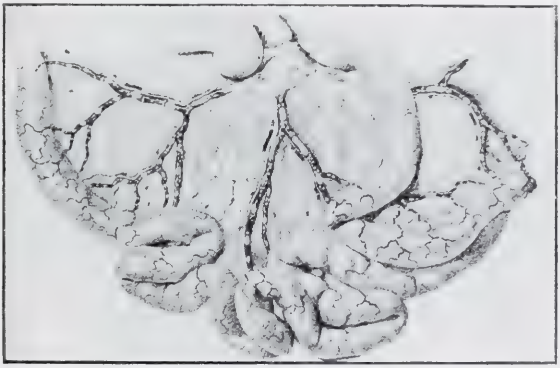

FIG. 59.—GAS BUBBLES IN THE ARTERIES AND VEINS OF THE INTESTINES (VON SCHRÖTTER).

A consideration of these experiments suggests that if the power of the cells to combine with oxygen be destroyed or injured, then not only nitrogen, but oxygen as well, would be liberated from solution and form emboli. In order to test this inference, M. Greenwood and the writer exposed frogs, mice, and rats to high oxygen pressures until they showed signs of paresis, and then rapidly decompressed them. In all cases they have obtained large quantities of free oxygen from the peritoneal cavities, subcutaneous tissues, and bloodvessels.

On one occasion three rats were exposed to +70 pounds of oxygen for an hour. Two were convulsed in thirty-five minutes, and at the end of the experiment all were moribund. One, however, still breathed after decompression, which occupied three and a half seconds. An analysis of its peritoneal gas gave 54·5 per cent. oxygen. In another experiment five rats were exposed to +75 pounds of oxygen for twenty-five minutes. All appeared to be affected, and one was convulsed. The pressure was reduced to +0 pound in four seconds, and several of the others were immediately thrown into spasms. One of the latter was killed for analysis, and yielded 67·9 per cent. oxygen and carbon dioxide, and 32·1 per cent. nitrogen.*

Since the lesions produced in animals by sudden decompression are known to be caused by the liberation of nitrogen bubbles from the blood and tissue fluids, it would seem probable that any animal whose respired gases are conveyed to the cells without the intervention of a circulating liquid should be immune from decompression symptoms. M. Greenwood put this to the test. In tracheal breathing invertebrata, such as the Lepidoptera, inspired air is conveyed directly to the body cells by branching tracheæ, the vascular system not apparently performing any respiratory functions. Lepidopterous larvæ are, accordingly, suitable material for experiment.

An active third year's larva of *Cossus* (the "Goat" moth) was twice submitted to a pressure of +25 to 30 atmospheres for periods of twenty minutes and two hours forty minutes respectively. The insect appeared quite normal and active during the experiment. Decompression was effected instantaneously, and produced no unfavourable effect on the larva, which has since pupated in a perfectly normal fashion. A control frog maintained at a similar pressure for forty minutes and decompressed rapidly died in a few seconds, exhibiting the ordinary signs of gaseous embolism.

On two larvæ of *Lasiocampa quercus* the following experiment was performed:

A was placed in the pressure chamber with some food plant, and raised to +30 atmospheres. During the experiment the larva consumed several of the leaves. After fifteen minutes the pressure was lowered rapidly. On removal, the insect was found to be dead, the gut being enormously distended with semi-digested leaves and air bubbles.

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* The oxygen contained some air.

On *B* a similar experiment was performed, but no leaves were put in the chamber. Sudden decompression did not lead to any unfavourable result. The insect has remained quite healthy, and pupated regularly, the resulting imago being normal.

Supposing the time under pressure to have been long enough to fill the tracheæ with air, it is clear that the suggested immunity from decompression effects must exist. At the instant of decompression it seemed to those watching the experiment that the larvæ swelled slightly, but this may have been due to small, wriggling movements.

In view of these results it is unlikely that the spiracular orifices are guarded by efficient valves.

FURTHER EXPERIMENTS ON LARVÆ.

Air.—1. Two *Bombyx rubi*, three *Smerinthus populi :* Forty minutes +20 atmospheres ; no ill effects ; four control frogs all full of bubbles.

2. Two *B. rubi* and one frog : +27 atmospheres for thirty minutes. Frog, usual symptoms ; larvæ not affected.

O_2.—Frog and two *S. populi :* +16 atmospheres of O_2. Frog convulsed in fifty minutes ; both larvæ motionless. After decompression, latter less responsive to electric and other stimulus than control larvæ. One died later (? due to malnutrition), the other recovered. Frog distended, convulsed.

Two frogs and two *B. rubi :* +20 atmospheres O_2. Thirty-three minutes ; larvæ appeared paralyzed on decompression, but recovered. Both frogs dead.

CHAPTER XIII

THE THEORY AND PRACTICE OF DECOMPRESSION

When a gas is brought into contact with a liquid, the liquid takes up the gas in simple solution (apart from chemical affinity) until a state of saturation is reached. The amount thus taken up depends on the coefficient of solubility of the gas in the liquid, the temperature of the liquid, and the pressure of the gas. The blood passing through the lungs is in contact with a wet film of protoplasm, which in its turn is in contact with the air breathed, and the blood takes up the gases of the air in solution in accordance with Dalton's law, and if exposed to compressed air, will dissolve oxygen and nitrogen in an amount, increased in proportion to the pressure.

The increased proportion of oxygen so taken up adds itself to the large amount of oxygen chemically found in the blood. The arterial blood normally carries away from the lungs about 18½ volumes of oxygen chemically bound with the hæmoglobin of the red corpuscles. For each atmosphere of air a little less than 0·5 per cent. of oxygen is simply dissolved in the plasma. Thus at 6 atmospheres about 3 per cent. of oxygen will be dissolved in the plasma, and at 12 atmospheres 5 per cent. Exposed to pure oxygen, the blood would take up five times as much, or 2·5 per cent. per atmosphere in solution. Thus at a pressure of 4 atmospheres of oxygen, nearly 10 per cent. of oxygen would be in solution, in addition to the 18½ chemically bound with the hæmoglobin. The hæmoglobin is almost saturated on exposure to air at 1 atmosphere, and therefore will chemically combine with little more oxygen on exposure to compressed air or oxygen.

Normally all the free oxygen in solution, and a good deal of that in combination (some 8 per cent.), disappears when the blood reaches the tissues, and is used up in the oxidative processes of the body. If there is more in solution, then less of that combined with the hæmoglobin will be used, and thus the blood in the veins comes to have the arterial colour which has been noticed in men working under high pressures. Suppose 2 or 3 atmospheres of oxygen is breathed, then there may be more oxygen in solution than is used by the tissues, and the tissues become flooded with free oxygen—an altogether abnormal condition. The excessive concentration of oxygen acts as a poison, and produces inflammation of the lungs and convulsions.

Under the ordinary pressure used in compressed-air works, the increased solution of oxygen in the blood is of no importance, excepting the fact that it gives the worker a better supply, and he, not lacking oxygen, works a little more easily.

Carbonic acid is present in the lungs to the extent of about 5·5 per cent. of an atmosphere. The compressed air makes no difference as regards the solution of CO_2 in the blood, since the pressure of the CO_2 in the lungs is kept constant by the breathing, whatever the total atmospheric pressure may be. (See Chapter III.)

The increased proportion of nitrogen taken up by the blood in compressed air passes to the tissues, which contain fat and water. About 66 per cent. of the body weight is water, and an average man contains 15 to 20 per cent. of fat. If we take 0·9 per cent. as the coefficient of solubility at body temperature for the watery part, and rather more than five times that amount for fat (Vernon), and suppose a man of 60 kilogrammes has 15 per cent. of fat, it follows that there will be 970 c.c. of nitrogen dissolved in his body at 1 atmosphere, or roughly 1,000 c.c. At 2 atmospheres there will be 2,000 c.c., at 3 atmospheres 3,000 c.c., at 4 atmospheres 4,000 c.c., and so on, supposing he is exposed long enough for the tissues to become saturated.

The importance of the fat is shown by the fact that an animal with 25 per cent. of fat takes up twice as much nitrogen as one with no fat (Boycott). The skinnier and harder the man, the less the tissue fluids, the less nitrogen will be dissolved.

When a man is suddenly exposed to compressed air, the blood passing through his lungs is at once saturated with nitrogen (or nearly saturated), and is carried to the tissues, and the nitrogen is shared between the blood and the extravascular tissues in proportion to their respective bulks. The blood returns to the lungs to be resaturated, and so goes round and round, gradually saturating the body. The mass of the blood in man is about 5 per cent. of the body weight, or one-twentieth. The fat, however, increases the relative bulk of the tissues, as far as the solution of nitrogen is concerned, and in the man with 15 per cent. of fat the effective bulk of the blood is reduced from one-twentieth to one-thirty-fifth of the whole body. The tissues are capable of dissolving thirty-five times as much nitrogen as the blood. In a fat man the blood forms about one-thirtieth of the body weight, and its effective bulk is much less ; and as during decompression the process of saturation is reversed, and the blood carries nitrogen from the tissues to the lungs, it follows that the blood is a much slower carrier in the fat than in the lean man.

It has been shown that in the young the proportion of the mass of the blood to that of the tissues is higher,* and therefore lean young men are best able to stand decompression after exposure to high pressures.

Assuming that the blood is evenly distributed and circulates at an even rate throughout the different parts of the body, and that the body is suddenly exposed to the excess of air pressure, the tissues at the end of one complete round of the circulation will have taken up, say, one-thirty-fifth of the amount required to saturate. At the end of the second round, one-thirty-fifth of thirty-four thirty-fifths, and so on (von Schrötter).

As Major Greenwood puts it, let us suppose that $1/p$ of the tissue liquids consists of blood, and that these liquids dissolve v volumes per cent. of nitrogen under normal conditions ; let us further *assume* that under a pressure of n atmospheres all the blood passing through the lungs comes into gaseous equilibrium with the alveolar air at once. Then at the end of one complete circulation of the blood we shall have in the whole body—

$$\frac{n\,v}{p}+\frac{(p-1)\,v}{p} \text{ volumes per cent. of nitrogen.}$$

After another circulation we shall have—

$$\frac{n\,v}{p}+\frac{p-1}{p}\left(\frac{n\,v}{p}+\frac{(p-1)\,v}{p}\right) \text{ per cent. of nitrogen ;}$$

and quite generally, after q circulations, we have—

$$n\,v-\left(\frac{p-1}{p}\right)^{q} \text{ volumes per cent. of gas.}$$

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* Dryer and Ray, Transactions of the Royal Society, 1911

Thus, to attain full saturation—that is, $n\ v$ volumes per cent. of dissolved nitrogen—q must be infinite.

In practice, however, the term $\left(\frac{p-1}{p}\right)$ diminishes rapidly at first, and is small for relatively low values of q.

The blood is assumed to circulate once a minute. If the calculation be made, it will be found that the tissues are about one-half saturated after twenty-three rounds of the circulation, three-quarters saturated after forty-six rounds, seven-eighths after sixty-nine rounds, and fifteen-sixteenths after ninety-two rounds. That is, one-half saturation occurs in about twenty-five minutes, and almost saturation in about ninety minutes (Haldane and Boycott).

The time which the blood takes to make a complete circulation is not definitely known. It varies considerably for different parts, according to their physiological needs. A rough idea of the average time can be formed thus (Haldane): The average venous blood returning to the right side of the heart has been found to have lost 6 to 8 per cent. by volume of its oxygen, while the air breathed loses about 4 per cent. by volume of its oxygen. Assuming that little oxygen is used in the lungs themselves, we may conclude that the volume of blood passing through the lungs is about half the volume of air breathed. The average volume of air breathed during rest is about 7 litres. Hence the blood circulated is about 3·5 litres. Roughly, therefore, the whole blood circulates about once a minute in the resting man. In a man doing work the respiratory use of oxygen may increase three, six, or even ten times, according to the hardness of the work. The circulation probably increases in the same proportion. Thus hard work accelerates saturation or desaturation three, six, or even ten times, and exercise during decompression is one of the best methods of expelling the nitrogen and preventing trouble.

Plesch calculates that the blood circulates in 55 seconds during rest, and in 4·5 seconds during the most strenuous exertion ; that the volume of blood circulated per minute in a resting man, weighing 70 kilogrammes, is 4·3 litres, and 47 litres when he is doing the most strenuous work.*

If only the blood had to be considered, it is clear that it would

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* "Hæmodynamische Studien," Berlin, 1909, p. 232.

become nearly saturated or desaturated in a minute or two of time, and there would be no danger of nitrogen bubbles forming. But the blood acts as a carrier to the tissues, and herein lies the complexity of the conditions. Just as in the lungs there is an exchange of gas by diffusion between the blood and lung air, so in the tissues there is an exchange between the gas in the blood and tissues—an exchange which takes place through the thin wall of the capillaries. The venous blood leaving the tissues will have about the same nitrogen pressure as in the tissues, and thus, in a man exposed to compressed air, while the arterial blood becomes almost saturated at once, the venous blood will not be saturated until the tissues are. Similarly, on decompression, while the arterial blood is almost desaturated after the passage through the lungs, the venous blood coming back to the heart will not be desaturated till the tissues are. Moreover, the desaturation of the tissues and the saturation of the venous blood will vary in different parts, because it has been ascertained that the blood is not distributed evenly to all parts of the body. The proportion of blood volume circulating per unit time to that of tissue supplied varies within very wide limits. Some parts, such as the heart, muscles in activity, the grey matter of the central nervous system, and the glands, have a far greater blood-supply than other parts, such as the connective tissues, fat, skin, joints, white matter of the nervous system, etc.

It is not possible to measure the saturation of most of the tissues directly under normal conditions. We have shown on ourselves that the kidney in a state of activity is about saturated in eight to ten minutes, as evidenced by estimation of the nitrogen gas dissolved in the urine. This can be taken as the measure of the rate of saturation of the quick organs. "As to the slow parts, some information can be gained from the practical experience of caisson workers. It seems perfectly clear from the experience of workers in caissons and tunnels that, other things being equal, the probability of bends, etc., occurring is very much less if the duration of exposure to compressed air is confined to one hour. As to longer periods of exposure, Mr. E. W. Moir, who has had very great experience on this subject, informs us "that he is confident from his observations that a limitation of the exposure to even three hours distinctly diminishes the risks of bends, as compared with six or eight hours' exposure" (Report of Admiralty Committee).

At the St. Louis Bridge Works the depth when rock was finally reached was 110 feet (+48 pounds). Out of 352 men employed, twelve were killed and eighteen seriously injured. The men were said to be decompressed in three to four minutes. There were no more fatal cases when the length of shift was reduced from four hours to one, and none suffered among the many visitors, including ladies, who were in the caisson only a short time.

Divers frequently come up from great depths in three to four minutes, and accidents only occasionally happen. This is because they stay down only a short time, and if the time be sufficiently reduced—say, to a minute or two—a diver can safely ascend in a minute from 25 to 30 fathoms.

" In diving for pearls and sponges at great depths, it appears to be the practice for the diver to sink rapidly to the bottom, remain there for two or three minutes, and then come rapidly to the surface."* When the destroyer *Chamois* sank in 32 fathoms (192 feet) off Patras, in the Mediterranean, in 1904, several Greek and Swedish divers descended repeatedly in order to examine the hull, so as to clear up the cause of the sudden disaster. They were able to get down for three or four minutes at a time, and to return as rapidly, without accident, although they did not succeed in their object. They were usually about ten minutes under water. The depth (about 32 fathoms) is the greatest to which we have been able to find any record of divers penetrating safely. The other case in which this depth is reported to have been reached proved fatal to the diver (Basset-Smith). Another diver, who is reported to have reached 34 fathoms, perished on returning to the surface.

" A remarkable case of immunity from symptoms, in spite of relatively rapid decompression, was that of the celebrated diver Alexander Lambert. Messrs. Siebe, Gorman and Co. (to whom we are indebted for information about Lambert and other of their divers) inform us that, during the salving of £70,000 worth of gold at a depth of 27 fathoms, he descended thirty-three times—usually twice and sometimes thrice per day. He stayed twenty to twenty-five minutes below, took two to three minutes in descending, and only four to five in ascending. In his last descent he, unfortunately, stayed down for forty-five

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* In the Pearl Fisheries off Broom (Australia) the pearlers walk for hours along the bottom, covering many miles as the luggers drift above them. They come up in a few minutes from 20 to 25 fathoms. The annual loss of life is 7½ per cent., and this compels them to keep to shallower and more fished-out waters.

minutes, and about half an hour after ascending he became completely paralyzed in the lower part of his body. From this attack he never completely recovered. His immunity, with only four or five minutes spent in decompression, in spite of a stay of twenty to twenty-five minutes on the bottom, was nevertheless very remarkable.

"Another equally remarkable record is that of Erostarbe, employed by the same firm. He succeeded in salving a quantity of silver at the great depth of 29 to 30 fathoms. During this work he made about seventy dives without injury, his time below water from the surface and back being strictly limited to twenty minutes, and latterly to fifteen minutes. He took three to five minutes to descend, and about three minutes to come up, so that he was on the bottom about eight to thirteen minutes. On one occasion he remained under water for forty minutes, and about fifteen minutes after returning he became very ill, suffering great pain. His condition seemed so serious that the Last Sacrament was administered to him. The skin of his legs, arms, and shoulder became black from extravasations of blood. He was quite well again a week later, and continued his work. . . .

"One of Messrs. Siebe, Gorman and Co.'s divers—A. Briggs—in salving gold coin at a depth of 27½ fathoms, made twelve dives, during each of which he spent about twelve minutes in the wreck, and occupied about ten minutes in descending and twelve minutes in ascending. Another diver—Rayfield—went recently to 30 fathoms in Loch Long, taking fifteen minutes to descend and twenty-one minutes to ascend. At the same place Diver W. R. Walker went for about the same time to 28 fathoms, and took about twenty minutes to ascend, with stops of about two and a half minutes every 5 or 6 fathoms. He had previously worked two shifts a day for three months continuously in 21 fathoms of water in a well in London, spending half an hour on the bottom at work, and taking twenty to twenty-five minutes in ascending. Another diver, G. Maycock, during light work at 22½ fathoms in a well in London, spent twenty minutes on the bottom, and came up in seven minutes. In a subsequent piece of work at Datchet Waterworks, in 100 feet of water, he was seized with 'pressure' in the legs and arms after working hard for forty-five minutes at the bottom, and coming up in five minutes."

Keays has analyzed the evidence obtained from 557,000 man shifts at the East River Tunnels. The variation in percentage of cases even when calculated from groups of 3,000 to 4,000 man shifts are very large—*e.g.*, eight-hour shift, May, 1907, 0·43 per cent. of cases; and January, 1907, 0·94 per cent. of cases. Other conditions—temperature, fatigue, diet, etc.—play a rôle, and it is a matter of chance whether the bubbles set free in the workers happen to produce symptoms or not. The workers carried out two three-hour shifts with an interval of three hours. The first three-hour shift gave 0·35 per cent. of cases, and nine dangerous or fatal, in about 43,600 man shifts; the second three-hour shift 0·72 per cent. of cases, and four dangerous or fatal. The sum of the two shifts is 1·07 per cent. of cases. The percentage in 10,700 shifts of eight hours was 0·62. Contrasting the first three-hour shift with the eight hours, there seems to be an advantage, but a disadvantage in the double three-hour shifts in the day, because this doubles the number of decompressions.

Bornstein* records that from +2 atmospheres after anything up to fifty minutes' exposure he was decompressed without suffering in ten seconds; in ten minutes after one to two hours; in twenty minutes after two to three hours; in forty minutes after four to five hours; but suffered from bends and shortness of breath if decompressed in forty minutes after seven to eight hours' exposure. He says the new workers were tried on a four-hour shift first, and several who stood this all right suffered after the eight-hour shift.†

In the results on goats obtained by Haldane, Boycott, and Damant, we see that, after short exposures up to ten minutes to +75 pounds, and decompression in one minute, there are two cases of illness in seventy-four goats; while after exposures of 30 to 240 minutes, and decompression by stages in 30 minutes, there are twenty-nine cases in sixty-two goats. If the decompression has been in one minute after the long exposures, the death-rate would undoubtedly have been very high. In their table there is no clear evidence that a 30-minute exposure is worse than a 60-minute, or that 240 minutes' exposure is worse than after 120 minutes; but 120 to 240 minutes' seems certainly worse than after 30 to 60 minutes' exposure.

To return now to the question of desaturation. The Ad-

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* At the Elbe Tunnel Works, Hamburg.

† *Berl. Klin. Wochenschr.*, 1910. No. 27.

miralty Committee conclude that, even after three hours' work in compressed air, some parts of the body are not fully saturated with nitrogen, and that these slow parts are not more than half saturated after one hour's exposure. It seems to the writer very unlikely that any important organ or part would remain unsaturated so long during active work, when the circulation and pulmonary ventilation are increased four or five times over the resting volume. No doubt certain parts, like joints, tendons, the subcutaneous and abdominal fat depots, are very slow parts; but the joints, tendons, and connective tissues are of no account so far as regards serious accident. Bubbles in these will cause "bends" and "screws" only. It is the fat which is dangerous, because of its high coefficient of solubility. It saturates slowly, and desaturates slowly, and by its bulk may add to the blood enough nitrogen to produce bubbles, if the decompression is too rapid. In the report of the Admiralty Committee we find the following considerations put forward, which are due to the perspicacity of Haldane:

"If the pressure were lowered suddenly, and no bubbles were liberated, desaturation of the tissues and venous blood would occur at the same rate as saturation. If the blood were evenly distributed, about 22 per cent. of the excess of nitrogen would disappear in five minutes, and about 50 per cent. in fifteen minutes. If the pressure had been 30 pounds, or 2 atmospheres, there would be no possibility of bubbles forming or increasing in size after seventy minutes, since the combined pressure of nitrogen, CO_2, and oxygen in the tissues and venous blood, would not equal the atmospheric pressure. As, however, the blood is not evenly distributed, it will be far longer before this point is reached in the case of some of the tissues; and practical experience agrees with this expectation, since the symptoms known as 'bends' and 'screws' (pains in the joints and muscles) may appear or increase in intensity several hours after decompression, if the period of exposure to compressed air has been considerable.

"It is evident that if the air pressure is lowered gradually and evenly, the nitrogen pressure in the tissues must lag farther and farther behind the fall in the pressure of the air, however slow the decompression may be. Let us assume that the blood and tissues are saturated at 40 pounds pressure, that the air pressure is lowered at the rate of 2 pounds per minute from

40 pounds, and that the blood is evenly distributed throughout the body. At the end of five minutes the air pressure will be 30 pounds, and during these five minutes the average pressure will have been 35 pounds. The nitrogen pressure in the tissues will now have fallen about 22·5 per cent., or, say, 20 per cent. of the difference between 35 and 40 pounds. It will therefore correspond to saturation at a pressure of 39 pounds of air, or 9 pounds above the actual pressure of the air. After the next five minutes the air pressure will be 20 pounds, while the nitrogen pressure in the tissues will correspond to $39 - \frac{39-25}{5} = 36{\cdot}2$ pounds of air, or 16·2 pounds above the actual pressure of the air. After the next five minutes the excess in the tissues will be 21·9 pounds, and when atmospheric pressure is reached it will be 26·5 pounds—certainly a dangerous excess. With the actual blood distribution in the living body this excess will, of course, be much greater in the case of some parts of the body, and much less in the case of others. For example, in the case of tissues which required an hour to become half saturated in the compressed air, and a correspondingly long time to reach full saturation, the excess would be 36 pounds.

"Experience seems to show clearly that even with rapid decompression there is practically no risk of symptoms from bubbles being liberated unless the air pressure exceeds about 20 pounds, and that even with 25 pounds symptoms are not common, though with higher pressures the liability very rapidly increases, and becomes very marked when a pressure of 30 pounds is exceeded. It therefore seems fairly safe to assume that practically no bubbles at all are liberated by the blood and tissues unless the pressure has exceeded 15 pounds, or 1 atmosphere above atmospheric pressure. Now, the *volume* of gas capable of being liberated on decompression to any given pressure is the same if the *relative* diminution of pressure is the same. Thus the volume of gas, if any at all were liberated, would be the same on decompression from 2 atmospheres of absolute pressure (15 pounds pressure by gauge) to 1 atmosphere (normal pressure), as it would be on decompression from 4 atmospheres absolute (45 pounds) to 2 (15 pounds), or from 8 atmospheres absolute (103 pounds pressure, or 38½ fathoms of sea water) to 4 (44 pounds, or 16½ fathoms). It therefore seemed very probable that there will be no appreciable liberation of bubbles with any of these pressure-diminutions, even when sudden. A number of experiments on animals, made by Dr. Boycott and Lieutenant Damant in the steel chamber at the Lister Institute, has so far borne out this hypothesis. Sudden drops of even 60 pounds were in several cases observed to be tolerated with impunity if the absolute pressure was not more diminished than to a third, whereas drops of 45 pounds with the absolute pressure diminished to a fourth caused very serious symptoms."

EXPERIMENTS TO SHOW THAT THE ABSOLUTE RANGE OF PRESSURE THROUGH WHICH DECOMPRESSION OCCURS MAY BE OF LESS IMPORTANCE THAN THE RELATIVE RANGE OF ABSOLUTE PRESSURE.

Pressure in Lbs. +.	Exposure in Minutes.	Decompression to Lbs. +.	Actual Fall of Pressure in Lbs.	Relative Reduction of Absolute Pressure.	Duration of Decompression in Minutes.	Number of Goats.	No Symptoms.	"Bends."	Severe Symptoms.	Death.
75	180	24	51	5/9	4	10	10	0	0	0
51	180	0	51	3/4	4	10	2	3	3	2
45	120	– 6	51	5/6	6	3	0	1	1	1
39	120	– 6	45	5/6	6	4	1	0	3	0
45	120	0	45	3/4	10	12	6	4	2	0

It appeared from nearly 200 experiments on the effects of a sudden drop from + 75 pounds to + 24 pounds, or + 27 pounds, that the reduction of absolute pressure may be rather more than half without any great risk to goats.

Major Greenwood and the writer have confirmed this so far as regards pigs. Pigs, in shape of body, structure of viscera, diet, etc., are far more comparable to man than are goats. They are fat, and therefore form comparatively bad subjects. Also they lie quiet, sleeping in the warm chamber, and cannot be aroused into activity, so as to hurry the circulation and respiration and quicken desaturation. What a pig of, say, 70 to 100 pounds weight can stand, we may be pretty sure a man can stand. Forty-seven pigs and nineteen goats were decompressed by us from + 75 to + 18 pounds in ten minutes, and twenty-seven pigs from + 90 to + 18 pounds in ten minutes. Only one pig out of all showed any ill effects on reaching + 18 pounds. Practical experience of caisson workers bears this out. Such a thing as the occurrence of symptoms during decompression is almost unknown. "On ne paie qu'en sortant" (Pol and Watelle).

It is to be concluded, then, that at any rate up to 5 to 6 atmospheres *the absolute air pressure can always be reduced to half the absolute pressure at which the tissues are saturated without risk.* "Thus," writes Boycott, "a man saturated at +75 pounds (90 pounds absolute) may be safely decompressed to +30 pounds (45 pounds absolute), or from +45 pounds (60 pounds absolute) to +15 (30 pounds absolute) in a few minutes, the difference of pressure urging the nitrogen out of the tissues into the blood, and so out of the body, is at first 45 pounds and 30 pounds respectively in the two cases. The rationale of safe, quick decompression is, then—(1) Never to allow the nitrogen pressure in the tissues to be more than twice the air pressure, and (2) to make the fullest use of the permissible difference of pressure to get the nitrogen out of the tissues."

According to Haldane and Boycott, the fallacies of uniform decompression are three—(1) No use is made of the possibility of hastening the exit of nitrogen from the tissues by putting on the greatest permissible stress; (2) however slowly uniform decompression is conducted, the difference between the tissue pressure and the air pressure must become larger and larger. Such a rate as twenty minutes per atmosphere is far too slow at first, and much too fast for the later stages. "Uniform decompression to be safe has to be so prodigiously slow that it is altogether an irrational proceeding." (3) The effective exposure to high pressures is prolonged. This only applies to short exposures.

Putting Haldane's theory of stage decompression to the test on goats, Boycott and Damant obtained the results given in the table on p. 208.

For the shorter exposures to +75 pounds up to thirty minutes, the advantage seems clear—stage, seven cases of "bends"; uniform, twenty-four "bends," four severe cases, and one death. Taking an exposure of 120 minutes, and decompression rate of 92-minute stage and 100 minutes uniform, we find three "bends" and one severe case for stage, and three "bends," five severe cases and one death for uniform. Here, again, the advantage seems a fairly definite one, but not so great as the theory would lead us to expect. Lastly, taking 180 minutes' exposure and 133 minutes' decompression, we see there are three cases of "bends" for stage and five for uniform (two of these are classified as doubtful or slight). There is no advantage here

SEVENTY-FIVE POUNDS POSITIVE PRESSURE.

Series.	Exposure in Minutes.	Decompression in Minutes.	Number of Animals.	Number of Experiments.	Stage Decompression.				Uniform Decompression.			
					No Symptoms =per Cent.	"Bends."	Severe Symptoms.	Death.	No Symptoms =per Cent.	"Bends."	Severe Symptoms.	Death.
A	15	31	18	34 stages 36 uniform	29=85	5	—	—	19=53	13	3	1
B	30	31	6	6	4=67	2	—	—	1=17	4	1	—
C	30	68	14	14	14=100	—	—	—	7=50	7	—	—
D	120	70	13	13	9=69	4	—	—	4=31	7	2	—
E	120	92 stages 100 uniform	19	19	15=79	3	1	—	10=53	3	5	1
F	180	133	10	10	8=80	2	—	—	5=50	5	—	—
			Total ..	96 stages 98 uniform	79=82	16	1	—	46=47	39	11	2

worth talking about, for the influence of chance is so great that a much greater number of animals and experiments is needed to settle the matter. We have seen wide variations in the East River Tunnel results, even when groups of some thousand shifts, conducted under the same conditions of pressure and decompression, are compared.

Major Greenwood and I, in our investigation on pigs, contrasted the two methods of decompression. The pressure and decompression time were the same as in Series E in Boycott and Damant's experiments. The pigs were decompressed one week by stage, and the next week by uniform; and as their increasing weight and fatness added to the risk, we started one set of pigs by the stage and another set by the uniform method. Our results were:

UNIFORM METHOD.

Exposure to + 75 lbs. 90 to 100 minutes.
Decompression in 100 to 109 minutes.
Average 98·8 minutes.

		Per Cent.	
Deaths	3	15	20
Dyspnœa	1	5	
Normal	16	80	
	20		

Average weight of pigs, 66·88 lbs.

STAGE METHOD.

		Per Cent.	
Deaths	3	9·375	34·375
Dyspnœa	8	25·000	
Normal	21	65·625	
	32		

Average weight of pigs, 75·25 lbs.

There is no proof to be found in these figures for the superiority of the stage method. In the case of some smaller pigs, weighing 33½ to 49 pounds, and decompression in thirty-seven to forty-five minutes, stage method killed four out of four, and uniform method four out of eight, with three severe cases.

To test rabbits by both methods we chose a decompression rate which gave a fair number of accidents. The rabbits were exposed to 100 pounds for one hour, and decompressed in eight minutes.

	Uniform Method.	Stage Method.
Deaths	18	22
Paralyses	3	11
Normal	107	102
	128	135

The duration of the stages used in these exposures were here made of the same relative proportion as those given in the Admiralty Committee's table.

So long, then, as a decompression time is chosen which is too short to be safe, we find in all these experiments no less a number of accidents by the stage method. According to the theory, we should certainly expect a better result. It is possible that the noise of rush of gas, by frightening the animals, disturbed the respiration and circulation at each stage of the decompression. The cold, too, produced at each stage may, by cooling the skin and constricting its vessels, be disadvantageous.

We tried a method of decompression continuous but lengthening in proportion as the pressure fell. This gave no better results than the uniform method.

Decompression continuous and progressively slowing.
Average time, 101·8 minutes.

		Per Cent.	
Deaths	4	10	25
Dyspnœa	6	15	
Normal	30	75	
	40		

Average weight of pigs, 64·89 lbs.

Boycott and Damant, in their experiments on the influence of fatness, decompressed guinea-pigs both by the stage and uniform method. The guinea-pigs were exposed for one hour to +100 pounds. After uniform decompression in four minutes, four survived, eight died. After uniform decompression in ten minutes, two survived, five died. After stage decompression in twenty-three and a half minutes, sixteen survived, six were ill, and eighteen died. After stage decompression in fifty minutes, three times over, eleven survived, one died. After stage decompression in thirty-four minutes three times, five survived, two ill, three died. The uniform and stage periods are not comparable, but the stage method is surprisingly ineffectual, considering the theoretical claims made for it. It is very doubtful whether uniform decompression in thirty-four or fifty minutes would have given worse results. Boycott and Damant attribute the relatively poor effect of the stage decompression to the low rate of respiratory exchange, the guinea-pig inhaling only 1·5 grammes CO_2 per 1,000 square centimetres of body surface per hour, against rather more than 2 per cent. for goats or dogs. On the other hand, the guinea-pigs only weighed 1 to 1½ pounds, while goats weigh 40 to 60 pounds.

Rats weighing 50 to 200 grammes (2 to 7 ounces) never die after a decompression made as short as five minutes. There are bodily conditions which make this great difference between guinea-pigs and rats, and it seems likely that the gas arising from fermentation in the bowels of the guinea-pig may contribute to this difference. So, too, in the case of the goat and pig. The pig, unlike the goat, never suffers from "bends." The difference between them is probably due to the smaller circulation in the legs of the goats, which are chiefly composed of thin tendon and bone.

The conclusion to be drawn, then, from experiments on animals is that there is evidence in favour of stage decompression after short exposures, but no decisive evidence of its superiority after long exposures. The theory is a very captivating one, but experiment has not brought that conclusive support which was to be expected, and there is no evidence to substantiate the statement quoted above: "Uniform decompression, to be safe, has to be so prodigiously slow that it is altogether an irrational proceeding."

Bornstein has compared the effect of stage and uniform method at the Elbe Tunnel Works, Hamburg (+2 atmospheres).

Days.	Workers.	Cases of Illness.
20 stage	526	15
16 uniform ..	528	17
18 stage	529	12
16 uniform ..	529	14
14 stage -.. ..	536	12

There is a slight advantage on the side of the stage method, but not one outside the limits of error. A far bigger number of observations are required. The exercise of climbing just after decompression gave a much greater freedom from "bends" than the substitution of the stage for the uniform method.

A large series of experiments are still required to settle the superiority which is claimed for the stage method after long exposures. A stage method is convenient, and therefore, not caring to waste our energies on such a series, we tested the stage method on pigs, and extended the time enough to make our results fairly good. We used a one-stage method, thus:

Exposure at + 75 lbs. for 90 minutes.
Decompression to + 20 lbs. in 10 minutes.
Pause at + 20 lbs. for 85 minutes (average).
Decompression to + 0 lbs. in 18·3 minutes (average).

		Per Cent.
Deaths	0	0
Dyspnœa	0	0
Normal	12	100
	12	

Average weight of pigs, 55 lbs.

Exposure at + 75 lbs. for 120 minutes.
Decompression to + 20 lbs. in 10 minutes.
Pause at + 20 lbs. for 102 minutes (average).
Decompression to + 0 lbs. in 14·3 minutes (average).

		Per Cent.	
Deaths	1	2·86	5·72
Dyspnœa	1	2·86	
Normal	33	94·29	
	35		

Average weight of pigs, 73·85 lbs.

A similar decompression of fat pigs (81 to 115 pounds weight) from + 90 pounds, allowing a pause of 105 to 120 minutes at + 20 pounds, gave unfavourable results—seven deaths and one severe case in twenty-seven pigs. It must be borne in mind that the pigs were very fat, and slept on the floor of the caisson during decompression. We tried to rouse them by giving them electrical shocks, but could not succeed in making them active.

On goats we carried out the following observations:

Exposure at + 50 lbs. for 3 to 4 hours.
Decompression to + 20 lbs. in 10 minutes.
Pause at + 20 lbs. for 30 to 40 minutes.
Decompression to + 0 lbs. in 8 to 10 minutes.

Normal	9
Symptoms	1
Deaths	0

Exposure at + 75 lbs. for 2 to 3 hours.
Decompression to + 20 lbs. in 10 minutes.
Pause at + 20 lbs. for 90 to 120 minutes.
Decompression to + 0 lbs. in 10 to 20 minutes.

Normal	13
Symptoms	5
Deaths	1

Exposure at + 90 lbs. for 2 to 4 hours.
Decompression to + 20 lbs. in 10 minutes.
Pause at + 20 lbs. for 120 to 150 minutes.
Decompression to + 0 lbs. in 10 to 20 minutes.

Normal	29
Symptoms	8
Deaths	1

Three goats, kept on a spare and dry diet, were compressed to 90 pounds for four hours, and safely decompressed by this method three times a week for three weeks.

Exposure at +90 lbs. for 2 hours.
Decompression to +20 lbs. in 10 minutes.
Pause at +20 lbs. for 90 minutes.
Decompression to +0 lbs. in 20 minutes.

Normal	0
Symptoms	0
Deaths	6

These goats had a good meal of wet food beforehand. After decompression to 20 pounds they were distressed ; their stomachs were blown out with gas.

The Admiralty Committee says : " One of the most striking features in all the animal experiments has been the great variability of the results." Certain goats, just as Caisson workers, are habitually immune. It was not altogether a question of age or size, for the oldest, largest, and fattest goat, " Pa," was very resistant, while one of the smallest and thinnest animals, " Little Billy," was soon prostrated with paralysis. Nannygoats were more susceptible to severe symptoms than billygoats. Greenwood and the writer have observed just the same individual differences among goats. On the other hand, among pigs, fatness has told far the most.

" With moderate or long exposures, both the proportion of animals showing illness and the severity of these illnesses are in relation to the rapidity and spacing of the decompression. But it appears likely that this applies only to animals which are fairly saturated or have taken up a material excess of gas. For if sudden decompression ensues immediately on, or very shortly after, reaching 75 pounds pressure, the animals show severe symptoms or none at all."

PRESSURE +75 POUNDS, COMPRESSION IN 5½ TO 6 MINUTES.

Actual Exposure in Minutes	Decompression in Minutes.	Goats.	No Symptoms.	" Bends."	Severe Symptoms.	Death.
1	1	6	6	—	—	—
3	1	5	4	—	1	—
6	1	6	6	—	—	—
10	1	7	6	—	1	—
15	1	6	2	2	1	1

The important conclusion is that " bends " do not follow such brief exposures to high pressures as may cause severe symptoms. It follows that " bends " must be the expression of phenomena which are not necessarily identical with those which in a more exaggerated form cause paralysis and death, and that the occurrence of " bends " is an indication that a fair degree of saturation has been reached. It seems justifiable to conclude that " bends " are the expression of the remoteness of the parts saturated, rather than the fact that saturation has occurred, and that, when once these remote parts of the body have taken up a material excess of air, extremely slow decompression would be required to escape that symptom altogether.*

Greenwood and the writer found that pigs do not suffer from " bends " at all. The only slight symptom they exhibit is itching of the skin, which leads them to scratch themselves against table-legs or anything handy after decompression. We are convinced that this itching is due to gas bubbles set free in the subcutaneous fat—bubbles which in some cases produce venous coloration and mottling of the skin, especially behind the ears. The bubbles in the fat prevent the animals bleeding white when they are killed, and this may be the case days after decompression. The pink coloration of the fat has deprived us of the chance of recuperating our expense by sale of the victims. No butcher would take a second pig from us, even at any price ; he got into such trouble from his customers over the sale of the first. The dead pigs had to be cut up and divided among the laboratory servants and their friends, who soon came to know the excellence of decompressed pig.

Apart from the itching, the pigs showed no other kind of minor symptoms. The severe symptoms they suffered from was dyspnœa, due to bubbles in the right heart, and pulmonary embolism.

The conclusion which the writer draws from the experiments of the Admiralty Committee, and their statement cited above, is that " bends " in goats are of little account in dealing with the statistical evidence derived from experimental trials of different methods of decompression. Many of the " bends " noted in goats by Boycott and Damant are classified as slight or doubtful. The Admiralty Committee admit that " bends " are the sign of the saturation of very slow parts, which will be very slow to

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* Admiralty Committee Report, p. 73.

desaturate. The severe symptoms are produced by want of adequate desaturation of quick parts or moderately slow parts. In the case of man "bends" can be cured by recompression, and the engineer cannot be expected to eliminate entirely "bends" by any practical method of decompression, but he ought to eliminate all severe symptoms such as paralysis, dyspnœa, and death.

We may recall here that Bert tried a few times methods of stage decompression. He exposed a dog to a pressure of +10 atmospheres for a time not definitely stated, perhaps about an hour. Decompression was effected in the following way: The pressure was rapidly lowered to +8 atmospheres, and maintained at this level for fifteen minutes; it was then diminished to +6 atmospheres, and another pause of a quarter of an hour occurred. This plan was followed throughout the decompression; after each drop of 2 atmospheres there was a pause of fifteen minutes, the whole process occupying one hour and ten minutes. On opening the cylinder the animal seemed well, but two or three minutes later gave vent to cries of pain. It subsequently moved the left forefoot, as if the limb were tender, but on the following day appeared quite well. Two days later the same animal was exposed to +10 atmospheres for fifteen minutes, and decompressed uniformly at the rate of eight minutes per atmosphere. It exhibited neither immediate nor remote symptoms.

Another dog was exposed to +10 atmospheres for seven minutes, decompressed to +6 atmospheres in two minutes, and, after a pause of twenty-eight minutes, decompressed in two minutes to +3 atmospheres. There was then an interval of twenty-six minutes, subsequent decompression being carried out in less than half an hour. No symptoms followed.

In summarizing his results, Bert (1878) writes: "I have remarked no great differences between the cases in which decompression was effected continuously at the rate of eight or ten minutes per atmosphere and those in which it was carried out by means of sudden jumps, with intervals of repose. The facts are not, however, sufficiently numerous to permit of deciding in favour of one or other of these methods."

CHAPTER XIV

THE THEORY AND PRACTICE OF DECOMPRESSION—*Continued*

The experimental evidence as to the relative safety of uniform and stage decompression on man may now be considered. The results show that a few slight cases of " bends " have occurred from the uniform method, which have been absent from the stage method. They do not by any means prove that great relative deficiency of the uniform method claimed by the theory of Haldane.

In 1894, at Bordeaux, H. Hersent, an engineer in charge of caisson works, having first experimented on animals, found three workmen willing to submit themselves to high pressures of air. These men were enclosed in a steel chamber, and the experiments were conducted under the observation of a commission, composed of five members of the Bordeaux Faculty of Medicine. Two of the workmen had had previous experience of compressed air.

In one experiment the subject was compressed to +4·800 kilogrammes per square centimetre (+68·27 pounds per square inch) in thirty-five minutes, remained under this pressure one hour, and was decompressed in two hours three minutes. On quitting the chamber the man experienced a few *picotements,* which lasted for half an hour, but no other unfavourable symptoms. In a second experiment a pressure of +5·000 kilogrammes (+71·16 pounds per square inch) was attained, without any subsequent ill effects beyond a few *picotements*.

Finally, the same subject was compressed to +5·400 kilogrammes (+76·81 pounds per square inch) in forty-five minutes, remained under the pressure one hour, and was decompressed in three hours three minutes. The effects are recorded in these words : " A ressenti peu de picotements, cela tient aux bains sulfureux pris les jours précédents."

Hersent safely decompressed the men after exposures of one hour in 26 minutes from +2½ atmospheres; in 46 minutes from +3 atmospheres; in 60 minutes from +3½ atmospheres; in 77 minutes from +4 atmospheres; in 100 minutes from +4½ atmospheres; in 150 minutes from +5 atmospheres; in 183 minutes from +5½ atmospheres. Hersent safely used a method which is theoretically the worst—viz., +5 to +4 atmospheres in 45 minutes; +4 to +3 in 35; +3 to +2 in 30; +2 to +1 in 20; +1 to +0 in 15. The decompression-rate was long at first and slow at the last. The men suffered from nothing but slight "bends" on one or two occasions.

Hersent's experiments justify his conclusion that "avec quelques précautions en sus de celles qu'on prend ordinairement, les hommes peuvent être comprimés et décomprimés sans danger pour leur vie, et que même leur santé n'est pas menacée quand on atteint des pressions allant jusqu'à 5 kg. 400."

Major Greenwood and the writer carried out experiments on themselves in a steel cylinder kindly placed at their disposal by Messrs. Siebe and Gorman, who also afforded an air compressor and skilled assistance.

This cylinder had a capacity of 42·2 cubic feet, and was provided with a mattress, blanket, and pillows, enabling the subject to adopt a comfortable attitude. Compression was effected by means of a two-cylinder pump driven by a gas engine, which could raise the pressure to +6 atmospheres in about forty minutes. Two decompression taps were provided, with fine bores, permitting very careful adjustment of the rate of escape. The chamber was also fitted with electric light, bell, telephone, and a thick glass observation window; the latter, however, was subsequently covered with a steel shutter for greater security. The pressure was measured by a Bourdon spring gauge, which had been tested for correctness. The measurements, etc., of the two subjects were: L. H., age thirty-nine, weight (in clothes) 87½ kilogrammes, height 1·81 metres, vital capacity 3,500 c.c., tidal air 510 c.c.; M. G., age twenty-five, weight 53 kilogrammes, height 1·65 metres, vital capacity 4,000 c.c., tidal air 300 c.c. Both were in good physical condition, but L. H.'s vital capacity was reduced by a previous attack of pleurisy. From this reason, and on account of his greater age, weight, and fatness, he was the less suitable of the two for high-pressure work. We shall now give an account of a typical experiment. The description is reproduced from notes taken at the time.

Experiment II. November 29, 1905.

The subject (M. G.) entered the chamber at 10.40 a.m. In order to avoid any accumulation of CO_2, a constant ventilation at the rate of 25 litres per minute was maintained.

Time.	Temperature of Chamber.	Pressure.	Notes.
A.M.	Degrees F.	Lbs.	
10.40	57	+0	
10.50	62	—	
10.55	—	+16	Voice becoming nasal and metallic.
11.5	67	—	
11.20	69	+62	Sensation of slight vertigo.
11.34	68*	+92†	
Between 11.25 and 11.40 articulation was difficult, and the subject experienced some trouble in making himself heard through the telephone.			
11.55	—	+77	
12 noon	65	—	
Subject quite comfortable, voice still nasal, but easier to produce, and much more audible.			
P.M.			
12.4	—	+72	
12.10	—	—	Pulse, 40. Respiration, 9 per minute.
12.37	64	+52	
1.0	63	+31	Voice much better.
1.20	63½	—	Pulse, 42.
1.51	—	+0	

Period of compression, fifty-four minutes.

Period of continuous decompression, two hours seventeen minutes.

On quitting the chamber some itching was perceived in both forearms, especially the right. In about twenty minutes neuralgic pains were felt, localized in the radial side of the left forearm. These pains gradually increased in intensity, spreading up the arm ; then, after remaining moderately intense for five minutes, they gradually subsided. Several minutes later (about one hour after leaving the chamber) similar pain was experienced in the right forearm. This, however, did not spread upwards, was less severe, and quickly subsided. An hour and a half after leaving the cylinder the subject felt quite well, and no subsequent ill effects resulted. As will appear later, there is good reason to suppose that the slight discomfort present at the conclusion of

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* Wet cloths were placed on the cylinder at this time to cool it.

† This reading was verified by Mr. J. A. Craw, who was present during the whole course of the experiment.

this experiment is attributable to the fact that the subject remained almost completely at rest during decompression. We therefore concluded that an adult may be safely submitted to a total barometric pressure of a least 7 atmospheres, which is, we believe, a limit higher than any previously reached.

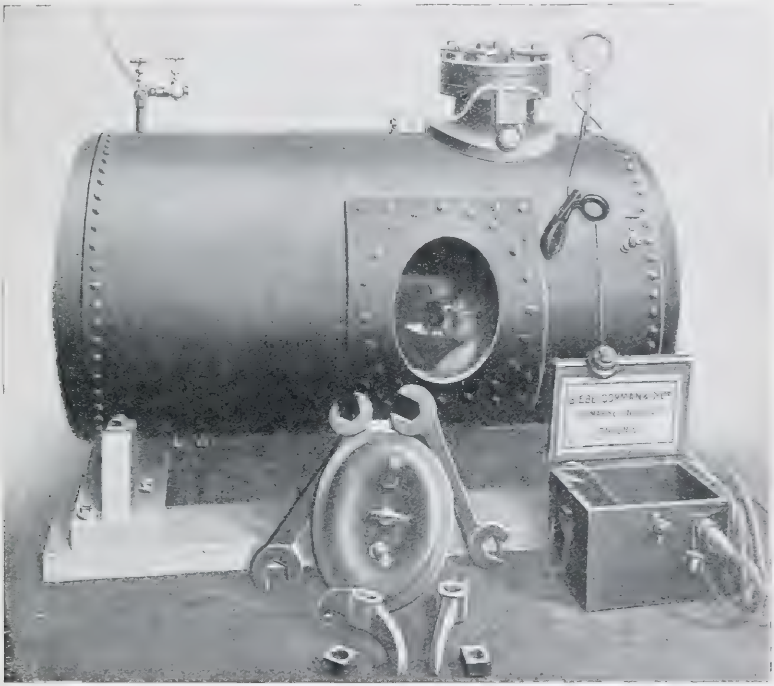

FIG. 60.—VIEW OF CYLINDER (OPEN) WITH WORKMAN INSIDE.

The chamber is fitted with—Electric bell, electric light, observation window, compression pipe, decompression tap, and telephone.

In the course of our investigation the following pressures have been obtained :

SUBJECT, L. H.	SUBJECT, M. G.
75 lbs., once.	92 lbs., once.
60 ,, twice.	75 ,, three times.
45 ,, ,,	60 ,, four ,,
30 ,, four times.	45 ,, five ,,
	30 ,, seven ,,

We came to the conclusion that it was an important matter, during the decompression to move in turn every muscle and joint of the body, and to change one's position frequently, so as to keep the capillary circulation active in every part. In the brain, spinal cord, and abdominal organs this circulation is kept active by the work of the respiratory pump. In the limbs, muscles, fat of the back and chest, on the other hand, the movement of the blood and lymph back to the heart depends mostly on changes of posture and the expressive action of contracting muscles. The following observations support these views:

In Experiment XIII. M. G. was decompressed from +75 pounds in ninety-five minutes. During decompression he flexed and extended all the limb joints at frequent intervals, with the exception of the knees. Subsequently pain and stiffness were detected in the knees and nowhere else.

In Experiment XIV. the same subject was decompressed from +5 atmospheres in 120 minutes. During the compression all the limb joints, including the knees, were repeatedly moved. No after-effects of any kind were experienced.

The most interesting experiment in this connection is No. XV. L. H. was decompressed from +5 atmospheres in 105 minutes, a pause of five minutes being made at each atmosphere. During the decompression movements of the joints and muscle of the limbs and back were carried out regularly. On emerging from the cylinder, beyond a few *picotements*, no unpleasant symptoms were noticed.

On the next day the subject wrote as follows: "The only place I did not move and massage was the front of the chest, where I have plenty of subcutaneous fat. In the evening painful places were felt in the subcutaneous tissues of the anterior thoracic region: one spot under each nipple, one across the right side of the chest about the level of the ensiform cartilage, another above the left axilla in front, and one over the right upper arm in front. A red or purplish rash appeared over these tender places. They felt like a spot in which a subcutaneous injection of water has been made. Next morning the tenderness was better, but still evident, and the rash was subsiding."

The Admiralty Committee record that Damant and Catto were compressed several times in the chamber at the Lister Institute previous to the carrying out of deep-diving experiments. "The subjects remained closed in the chamber for half an hour after each experiment, the engine being also kept running so that recompression could be at once begun if any serious symptom developed. In addition to the actual period of exposure, the virtual period of exposure was calculated on the assumption that about half the time occupied in compression must be added. In view of the results with goats, the occurrence of decompression symptoms seemed probable in the more severe experiments. No symptoms were, however, observed, except considerable itching of the skin of the forearms where it was uncovered."

Pressure.	Actual Exposure.	Virtual Exposure.	Stage Decompression.
Lbs.	Minutes.	Minutes.	Minutes.
+39	60	69	24
+50	27	39	34
+55	19	33	31
+60	20	36	37½
+67	18	36	36
+74	15	35	42
+80	12	34	51

The following is taken from a Diary of the deep-diving experiments carried out off Rothesay, Isle of Bute, from H.M.S. *Spanker*, August, 1906.

" *Monday, August* 20.—H.M.S. *Spanker* arrived at Rothesay about 7 p.m., and was met by Drs. Haldane and Rees, and Mr. Catto, Gunner R.N. Arrangements were made to commence experiments the following day.

" *Tuesday, August* 21.—All the pumps to be used in the experiments were tested up to a pressure of 200 feet, and the leakage at this pressure measured. The pressure-gauges, which had been specially graduated for these experiments, were tested, and found to give correct readings. The method of testing employed was to attach the free end of the diving hose to a lead-line, and lower it over the side into the sea to the required depth. The pumps were then hove round until there was a free supply of air, and then stopped whilst the reading of the gauge was taken.

" The recompression chamber was tested on the Whitehead torpedo charging column, and it was found that the pressure could be brought up to 40 pounds on the gauge in three minutes. There was a leak of 1 pound per minute, or, roughly, 3 cubic feet. Afterwards Drs. Haldane and Rees were compressed up to about 30 pounds in order to further test the working of the chamber.

" Two double pumps were used for each diver in these and the subsequent dives. The divers were perfectly comfortable in moving about on the bottom. It may be mentioned that Lieutenant Damant had not dived previously beyond about 19 fathoms, and had no experience in diving except what he had gained in his course of instruction as a gunnery officer and in experimenting at Portsmouth for the Committee. Mr. Catto had much previous experience in diving work, but had never dived beyond 23 fathoms.

"The diver was connected by telephone with the deck of the *Spanker*. This was a convenience in many ways, particularly when samples were being taken, or work experiments carried out, and when one of the divers got foul. During his ascent the diver was stopped at each stage by signalling on the breast-rope in the ordinary way. The gauge was watched during the ascent; and when the depth indicated by it was within about 10 or 20 feet of the proper stopping-place, the pumps were stopped, and the gauge tapped until it reached the proper indication, whereupon the diver was stopped by signal. There was never the slightest difficulty in stopping him at the right point within a foot or two. It was necessary to stop the pumps, as, owing to the resistance in the pipes, the depth shown by the gauge was several feet beyond the actual depth. The gauges had been specially tested, and were correctly graduated for fresh water. Thus, with the diver sitting on the bottom, at an actual depth of just over 35 fathoms, or 210 feet, as carefully measured on the shot-rope with a standard measure, the gauges showed a depth of 216 feet with the pumps stopped, and 220 feet with them going. A pressure of 216 feet of fresh water corresponds almost exactly to 210 feet of sea water.

"The experiments were conducted from the deck of a torpedo gunboat, about 8 feet above water-level. The diver had thus to climb some 8 or 10 feet of ladder before even his 40-pound breast and back weights were removed, the total load being 155 pounds."

The severe excess taken in this climb must have materially aided the desaturation of the body.

"*Friday, August* 31.—H.M.S. *Spanker* moved down to the entrance of Loch Striven, where 35 fathoms of water could be obtained.

"In the morning Lieutenant Damant was the diver. Pumps Nos. 2,593, 3,604, and 3,592, were tested and used. Six hands were told off for each pump in reliefs of five minutes.

Time.	Remarks.
11.8	Glass screwed up.
11.8¼	Diver under water.
11.9	,, down 80 feet.
11.9¼	,, ,, 120 ,,
11.9½	,, ,, 150 ,,
11.9¾	,, ,, 180 ,,
11.10¼	,, ,, 200 ,,
11.10½	,, ,, 216 ,, on the bottom. Revolutions kept at 30 per minute, and the diver had a good supply of air.
11.13½	Diver took samples seated on the shot at the bottom of the rope.
11.15½	,, called up.
11.16¼	,, started up.
11.17	,, at 190 feet.
11.18	,, ,, 110 ,, Diver stopped to blow off sampling tube.
11.20½	,, ,, 90 ,, 1st stop.
11.23½	,, ,, 70 ,, 2nd ,,
11.28½	,, ,, 52 ,, 3rd ,,
11.33½	,, ,, 42 ,, 4th ,,
11.39½	,, ,, 32 ,, 5th ,,
11.44½	,, ,, 22 ,, 6th ,,
11.54½	,, ,, 11 ,, 7th ,,
12.4½	,, called up.

"There was no light on the bottom, which was of soft mud. The depth by the shot-line was 210 feet. Pressure was 93½ pounds. The gauge showed a pressure of 216 feet of fresh water with the pumps stopped, and 220 feet whilst they were heaving. The actual depth, as carefully measured on the shotted rope against the ship's standard measure, was just over 35 fathoms (210 feet).

"In the afternoon Mr. Catto made the same descent, and reached 35 fathoms. He found that the air-supply was more than ample. He walked out to the end of his distance line, and then took a sample of the air in his helmet.

Time.	Remarks.
2.12	Screwed up glass. Same pumps as last.
2.12¾	Diver under water.
2.14¾	Diver on the bottom. Revolutions reduced to 24, as the diver found the supply too much. He proceeded to the end of his distance line before taking his sample.
2.20½	Diver started up.
2.27¾	,, at 90 feet. 1st stop.
2.30⅓	,, ,, 70 ,, 2nd ,,
2.35¾	,, ,, 50 ,, 3rd ,,
2.40¾	,, ,, 40 ,, 4th ,,
2.45¾	,, ,, 30 ,, 5th ,,
2.50¾	,, ,, 20 ,, 6th ,,
3.0¾	,, ,, 10 ,, 7th ,,
3.10¾	,, called up.

“ *Tuesday, August* 28.—In the afternoon Mr. Catto was in the dress. Pumps Nos. 3,588 and 3,592 were used.

Time.	Remarks.
2.17	Glass screwed up.
2.18¼	Diver down 60 feet.
2.19	,, ,, 100 ,,
2.19¾	,, ,, 180 ,, on the bottom. The diver took down with him a wire hawser to shackle on to a sinker.
2.31¾	Diver called up, but could not come up, as he was foul, until—
2.48½	,, started up.
2.50½	,, at 140 feet.
2.53	,, ,, 100 ,, 1st stop.
2.56	,, ,, 80 ,, 2nd ,,
3.1	,, ,, 60 ,, 3rd ,,
3.7	,, ,, 50 ,, 4th ,,
3.12	,, ,, 40 ,, 5th ,,
3.22	,, ,, 30 ,, 6th ,,
3.37	,, ,, 20 ,, 7th ,,
3.52	,, ,, 15 ,, 8th ,,
4.0	,, ,, 10 ,, 9th ,,
4.18½	,, on the surface.

“ Mr. Catto attempted to shackle a hawser on to the sinker. He found the sinker without the slightest difficulty, and then, having tied his distance line to it, went back to the hawser. He found this in bights, and he seems to have got within the coils, and in trying to find the end of the wire to have fouled his life-line. When called up he could not get away, and it was twenty minutes before he could clear himself. In all he was down twenty-eight and three-quarter minutes in 30 fathoms of water. The rate of the pumps could not be kept up above 24 revolutions per minute, and the supply of air was not adequate to his exertions to free himself, so that he was almost overcome by the excess of CO_2. On account of his long exposure during heavy work, great care was taken in decompressing him, one and a half hours being allowed. There were no ill effects.

“ *Thursday, August* 30.—H.M.S. *Spanker*, off Loch Riddon. Mr. Catto made another descent under the same conditions, and shackled on the hawser to the sinker in four minutes after reaching the bottom. The revolutions of the pump averaged 24 to 30 per minute. The day was very bright, with the sun shining on the water, so that the diver saw with comparative ease in the water.”

We may now seek to find an explanation for the individual differences observed in animals and caisson workers, and the delay which is often seen to follow decompression before symptoms appear.

One factor is the colloidal nature of the blood, which opposes the formation of bubbles. Another is the amount of fat in the blood, chyle, and such an important blood-holding organ as the liver; this varies greatly with the amount of fat eaten. The liver may hold one-quarter of the blood. The fat may vary from 3 to 11 per cent. in chyle, and reach 10 per cent. or more in the liver. A third factor is the amount of fermentation and swallowed gas in the guts. It is probable that this gas acts as a starting-point for setting free of bubbles in the blood. The gas in the distended guts may be squeezed into the capillaries. It has been proved possible to force air into the blood by blowing out the lungs or the bladder with air. Similarly, if the gut be distended with gas on decompression, some of this may pass into the blood and start the effervescence. The distension of the guts with gas will seriously interfere with the circulation in the abdomen, and this enhances the risk.

Supersaturated solutions will not froth unless "points" are given for the bubbles to form on. Bubbles themselves may act as points on which the other bubbles fasten.

We have studied the behaviour of colloidal solutions, oil, solutions of salts and water, supersaturated by exposure to several atmospheres, and then rapidly decompressed.

The following observations made by J. F. Twort and myself show how water behaves when reduced from +90 to +20 pounds, and either left quiet or gently shaken:

WATER SHAKEN FOR THIRTY MINUTES AT +90 POUNDS.

Dissolved Air found.	Dissolved Air at +90 lbs., calculated.	Dissolved Air at +20 lbs., calculated.	When collected.
15·10	15·71	—	at +90 lbs.
14·90	15·28	—	at +90 lbs.
14·42	15·88	5·26	at +20 lbs.
9·26	15·28	5·06	after 2 hours at +20 lbs.
9·78	15·74	5·16	after 2 hours at +20 lbs.
8·26	16·35	5·41	after oscillation for 15′ at +20 lbs.
10·47	15·73	5·21	after oscillation for 5′ at +20 lbs.
6·07	16·19	5·36	after oscillation for 30′ at +20 lbs.

On gentle oscillation the gas is given off without bubbling. Bubbles only occurred when the water was roughly shaken.

This shows how stage decompression is safe as far as regards the watery part of the blood. Oil, on the other hand, bubbles when left quite at rest. The oil, of course, has five times the amount of air dissolved in it.

In the case of colloidal solutions it requires much more shaking to get the bubbles out of the liquid than is the case with water. The more viscous the solution the more difficult is it for the bubbles to escape.

In the case of water we noticed the bubbles formed round particles of dust, or any points offered by the metal or rubber washers within the chamber. The dust particles were carried to the surface by the bubbles, and might discharge there and sink again. The influence of " points " may be seen on dropping pieces of broken stone into a glass of soda water. The energy required to separate a bubble of free gas from solution of a gas in a liquid is very considerable. Saline or colloidal solutions may hold gas in solution at differences of pressure of 25 atmospheres, so long as they are unshaken and free from points.

It is rare to find bubbles in the urine in animals killed by rapid decompression, but the urine effervesces at once when spilt on to a rough surface or on being drawn into a glass. The amniotic fluid in a pregnant animal, on the other hand, more often has some bubbles in it, no doubt because of the movements of the fœtus. " Points," such as dust particles, alter the surface energy and allow the gas particles to run together and form bubbles.

The moving corpuscles in the blood perhaps act as " points " to a slight extent, and so make the blood the seat of election for the formation of bubbles. The colloidal nature of the body fluids, and the absence of " effective points," make for the harmless supersaturation and the safety of the caisson worker. The greatest danger is the formation of the first bubbles, for these act as " points." As has been said above, the gas in the intestine may be a starting-point, and the amount of fat in the blood chyle, liver, etc., may be a factor in helping to explain individual susceptibility.

It is a remarkable fact that bubbles, even the smallest, when they form, are of a size visible to the naked eye—*e.g.*, 0·2 millimetre. There are forces which prevent the formation of smaller bubbles.

Mr. J. F. Twort and the writer have measured the bubbles with a microscope and micrometer eye-piece, and studied their behaviour during recompression. The results, plotted out as curves, show that the volume of the bubbles varies inversely as the pressure (Boyle's law), and that the surface tension due to the skin of the bubble has no disturbing influence worthy of note. When the small bubbles run together to form larger ones, we found these large bubbles did not go into solution on recompression up to the full saturation pressure ; they expanded again on renewed decompression. This observation explains why on using recompression as a method of cure it is necessary to allow much time, and decompress the men very slowly and cautiously.

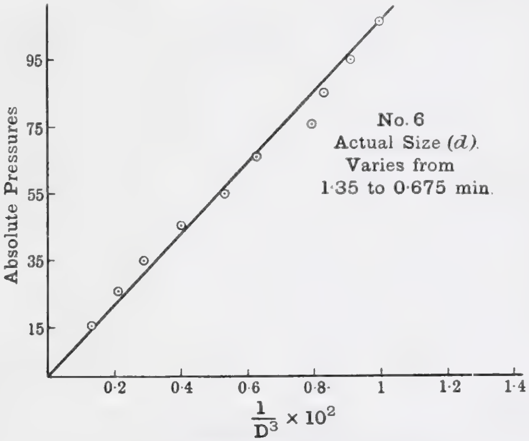

FIG. 61.—COMPRESSION OF A BUBBLE.

The reciprocals of the cube of the diameter of a bubble are plotted out at the different pressures. The results lie on a straight line, showing that Boyle's law holds good.

Based on Haldane's theory and on Boycott and Damant's experiments on goats, the Admiralty Committee have issued the table (p. 228) which now controls the diving in the Service, both as to the period of compression and decompression.

The divers are very properly directed to go down as quickly as possible, so as to shorten the time of exposure.

It has been found by trials made by Damant and Catto that it is quite possible to go down the shotted rope to a depth of 200 feet in two minutes. The only point to see to is that the Eustachian tubes are open during the first part of the descent, so that there is no trouble from unequal pressure on either side of the drum of the ear. The ear troubles are proportional to

TABLE OF STAGE DECOMPRESSION AND ORDINARY TIME LIMITS (ADMIRALTY COMMITTEE).

Depth.		Pressure Pounds per Square Inch.	Time under Water, *i.e.*, from Surface to Beginning of Ascent.	Stoppages in Minutes at Different Depths.						Total Time in Minutes for Ascent.	Number of Cylinders needed. *†	Revolutions of Pump per Minute.*
Feet.	Fathoms.			60 ft.	50 ft.	40 ft.	30 ft.	20 ft.	10 ft.			
0–36	0–6	0–16	No limit	—	—	—	—	—	—	0–1	1	15–20
36–42	6–7	16–18½	Up to 3 hrs.	—	—	—	—	—	—	1–1½	1	25–30
			Over 3 hrs.	—	—	—	—	—	5	6		
42–48	7–8	18½–21	Up to 1 hr.	—	—	—	—	—	—	1½	1	30
			1 to 3 hrs.	—	—	—	—	—	5	6½		
			Over 3 hrs.	—	—	—	—	—	10	11½		
48–54	8–9	21–24	Up to 30 mins. ..	—	—	—	—	—	—	2	2	20
			30 mins. to 1½ hrs. ..	—	—	—	—	—	5	7		
			1½ to 3 hrs.	—	—	—	—	—	10	12		
			Over 3 hrs.	—	—	—	—	—	20	22		
54–60	9–10	24–26½	Up to 20 mins. ..	—	—	—	—	—	—	2	2	25
			20 to 45 mins. ..	—	—	—	—	—	5	7		
			45 mins. to 1½ hrs. ..	—	—	—	—	—	10	12		
			1½ to 3 hrs.	—	—	—	—	5	15	22		
			Over 3 hrs.	—	—	—	—	10	20	32		
60–66	10–11	26½–29½	Up to 15 mins. ..	—	—	—	—	—	—	2	2	25
			15 to 30 mins. ..	—	—	—	—	—	5	7		
			30 mins. to 1 hr. ..	—	—	—	—	3	10	15		
			1 to 2 hrs.	—	—	—	—	5	15	22		
			2 to 3 hrs.	—	—	—	—	10	20	32		

66-72	11-12	29½-32	Up to 15 mins. ..	—	—	—	—	—	2	4	2	25
			15 to 30 mins. ..	—	—	—	—	3	5	10		
			30 mins. to 1 hr. ..	—	—	—	—	5	12	19		
			1 to 2 hrs. ..	—	—	—	—	10	20	32		
72-78	12-13	32-34½	Up to 20 mins. ..	—	—	—	—	—	5	7	2	25
			20 to 45 mins. ..	—	—	—	—	5	15	22		
			45 mins. to 1½ hrs. ..	—	—	—	—	10	20	32		
78-84	13-14	34½-37	Up to 20 mins. ..	—	—	—	—	—	5	7	2	30‡
			20 to 45 mins. ..	—	—	—	—	5	15	22		
			45 mins. to 1¼ hrs. ..	—	—	—	—	10	20	32		
84-90	14-15	37-40	Up to 20 mins. ..	—	—	—	—	3	5	10	2	30‡
			20 to 40 mins. ..	—	—	—	—	5	15	22		
			40 to 60 mins. ..	—	—	—	3	10	15	30		
90-96	15-16	40-42½	Up to 20 mins. ..	—	—	—	—	3	5	11	2	30‡
			20 to 35 mins. ..	—	—	—	—	5	15	22		
			35 to 55 mins. ..	—	—	—	5	10	15	32		
96-108	16-18	42½-48	Up to 15 mins. ..	—	—	—	—	3	5	11	4	20
			15 to 30 mins. ..	—	—	—	3	7	10	23		
			30 to 40 mins. ..	—	—	—	5	10	15	33		
108-120	18-20	48-53½	Up to 15 mins. ..	—	—	—	2	3	7	15	4	20
			15 to 25 mins. ..	—	—	—	5	5	10	23		
			25 to 35 mins. ..	—	—	—	5	10	15	33		

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[*] These figures are calculated on the supposition that the pump does not leak more than 20 per cent. at pressures up to 60 lbs.

[†] *I.e.*, using a Siebe-Gorman two-cylinder double-acting pump.

[‡] If found difficult to maintain 30 revolutions, another cylinder may be used instead.

TABLE OF STAGE DECOMPRESSION AND ORDINARY TIME LIMITS (ADMIRALTY COMMITTEE)—*Continued.*

Depth.		Pressure Pounds per Square Inch.	Time under Water, *i.e.*, from Surface to Beginning of Ascent.	Stoppages in Minutes at Different Depths.						Total Time in Minutes for Ascent.	Number of Cylinders needed.* †	Revolutions of Pump per Minute.*
Feet.	Fathoms.			60 ft.	50 ft.	40 ft.	30 ft.	20 ft.	10 ft.			
120–132	20–22	53½–59	Up to 15 mins. ..	—	—	—	2	5	7	17	4	25
			15 to 30 mins. ..	—	—	—	5	10	15	33		
132–144	22–24	59–64½	Up to 12 mins. ..	—	—	—	3	5	5	16	4	25
			12 to 25 mins. ..	—	—	2	5	10	12	32		
144–156	24–26	64½–70	Up to 10 mins. ..	—	—	—	3	5	5	16	4	25
			10 to 20 mins. ..	—	2	3	5	8	10	31		
156–168	26–28	70–75	Up to 10 mins. ..	—	—	2	3	5	5	18	4	30‡
			10 to 16 mins. ..	—	2	3	5	7	10	30		
168–180	28–30	75–80½	Up to 9 mins. ..	—	—	2	3	5	5	18	4	30‡
			9 to 14 mins. ..	—	2	3	5	7	10	30		
180–192	30–32	80½–86	Up to 13 mins. ..	—	2	3	5	7	10	30	6	25
192–204	32–34	86–91½	Up to 12 mins. ..	2	2	3	5	7	10	32	6	25

* These figures are calculated on the supposition that the pump does not leak more than 20 per cent. at pressures up to 60 lbs.

† *I.e.*, using a Siebe-Gorman two cylinder double-acting pump.

‡ If found difficult to maintain 30 revolutions, another cylinder may be used instead.

EXTRA PRECAUTIONS AFTER A SECOND DESCENT.—If a diver descends a second time into *deep water* with an interval of less than 1½ hours between the two dives, his body will be more highly saturated with nitrogen at the end of the second dive, and extra care is needed in bringing him up. A safe rule is to add together the times on the bottom in the two dives, and use the corresponding precautions shown in the tables. The extra time is, however, only needed for the second half of the stoppages.

TABLE SHOWING STOPPAGES DURING ASCENT AFTER EXCEEDING THE ORDINARY LIMITS OF TIME ON THE BOTTOM.

Depth.		Pressure in Pounds per Square Inch.	Time from leaving Surface to Beginning of Ascent.	Stoppages in Minutes at Different Depths.								Total Time in Minutes for Ascent.
Feet.	Fathoms.			80 ft.	70 ft.	60 ft.	50 ft.	40 ft.	30 ft.	20 ft.	10 ft.	
66	11	29½	Over 3 hrs.	—	—	—	—	—	—	10	30	42
72	12	32	2 to 3 hrs.	—	—	—	—	—	—	10	30	42
			Over 3 hrs.	—	—	—	—	—	—	20	30	52
78	13	34½	1½ to 2½ hrs.	—	—	—	—	—	—	20	30	52
			Over 2½ hrs.	—	—	—	—	—	—	30	30	62
84	14	37	1¼ to 2 hrs.	—	—	—	—	—	—	15	30	47
			2 to 3 hrs.	—	—	—	—	—	5	30	30	67
			Over 3 hrs.	—	—	—	—	—	10	30	35	77
90	15	40	1 to 1½ hrs.	—	—	—	—	—	5	15	25	47
			1½ to 2½ hrs.	—	—	—	—	—	5	30	30	67
			Over 2½ hrs.	—	—	—	—	—	20	35	35	92
96	16	42½	55 mins. to 1½ hrs.	—	—	—	—	—	5	15	30	52
			1½ to 2½ hrs.	—	—	—	—	—	10	30	35	77
			Over 2½ hrs.	—	—	—	—	—	30	35	35	102
108	18	48	40 mins. to 1 hr.	—	—	—	—	—	10	15	20	48
			1 to 2 hrs.	—	—	—	—	5	15	25	35	83
			Over 2 hrs.	—	—	—	—	15	30	35	40	122
120	20	53½	35 mins. to 1 hr.	—	—	—	—	5	10	15	25	57
			1 to 2 hrs.	—	—	—	—	10	20	30	35	97
			Over 2 hrs.	—	—	—	—	30	35	35	40	142

TABLE SHOWING STOPPAGES DURING ASCENT AFTER EXCEEDING THE ORDINARY LIMITS OF TIME ON THE BOTTOM—*Continued.*

Depth.		Pressure in Pounds per Square Inch.	Time from leaving Surface to Beginning of Ascent.	Stoppages in Minutes at Different Depths.								Total Time in Minutes for Ascent.
Feet.	Fathoms.			80 ft.	70 ft.	60 ft.	50 ft.	40 ft.	30 ft.	20 ft.	10 ft.	
132	22	59	30 to 45 mins.	—	—	—	—	5	10	15	20	53
			45 mins. to 1½ hrs.	—	—	—	5	10	20	30	30	98
			Over 1½ hrs.	—	—	—	15	30	35	40	40	163
144	24	64½	25 to 45 mins.	—	—	—	3	5	10	15	25	61
			45 mins. to 1½ hrs.	—	—	—	10	10	20	30	35	108
			Over 1½ hrs.	—	—	—	30	30	35	40	40	178
156	26	70	20 to 35 mins.	—	—	—	3	5	10	15	20	56
			35 mins. to 1 hr.	—	—	—	7	10	15	30	30	95
			Over 1 hr.	—	—	20	25	30	35	40	40	193
168	28	75	16 to 30 mins.	—	—	—	3	5	10	15	20	56
			30 mins. to 1 hr.	—	—	3	10	10	15	30	30	101
			Over 1 hr.	—	5	25	25	30	35	40	40	203
180	30	80½	14 to 20 mins.	—	—	—	3	3	7	10	15	41
			20 to 30 mins.	—	—	2	2	3	10	15	25	60
			30 mins. to 1 hr.	—	3	3	7	10	20	30	35	111
			Over 1 hr.	—	15	25	30	30	35	40	40	218
192	32	86	13 to 20 mins.	—	—	—	3	3	7	15	15	46
			20 to 30 mins.	—	—	3	3	5	10	15	25	64
			30 mins. to 1 hr.	—	3	5	10	12	20	30	35	118
			Over 1 hr.	5	20	25	30	30	35	40	40	228
204	34	91½	12 to 20 mins.	—	—	3	3	5	7	10	20	51
			20 to 30 mins.	—	3	3	3	5	10	20	20	67
			30 mins. to 1 hr.	3	3	5	10	15	20	30	35	124
			Over 1 hr.	15	20	25	30	30	35	40	40	238

diminution in volume of air in middle ear, and therefore diminish as the pressure increases. The directions which used to be given to go down slowly to big depths are quite wrong. The safety of the diver is greatly enhanced by quick descents and short exposures.

The next table shows the rates of decompression advocated by Haldane for caisson workers :

HALDANE'S RATE OF DECOMPRESSION IN CAISSON AND TUNNEL WORKS.

Working Pressure, in Pounds per Square Inch.	Number of Minutes for Each Pound of Decompression after the First Rapid Stage.		
	After First 3 Hours' Exposure.	After Second or Third 3 Hours' Exposure, allowing an Interval for a Meal.	After 6 Hours or More of Continuous Exposure.
18 to 20	2	3	5
21 ,, 24	3	5	7
25 ,, 29	5	7	8
30 ,, 34	6	7	9
35 ,, 39	7	8	9
40 ,, 45	7	8	9

Thus, if the pressure is 40 pounds gauge, decompress rapidly from 40 pounds to $\frac{40+15}{2}=27\frac{1}{2}$ pounds, absolute, or $12\frac{1}{2}$ pounds gauge, in three minutes, and then take seven minutes for each remaining pound—viz., $12\frac{1}{2}$ pounds, or $87\frac{1}{2}$ minutes $+3$ minutes $=90\frac{1}{2}$ minutes, or one and a half hours in all for a three-hour immersion ; or, for a six-hour immersion, 115 minutes in all.

Japp well asks : "Are the times suggested by Haldane practical ? Many caissons of small dimensions are sunk under air-pressures of 35 pounds, and to cramp men in a small air-lock for seventy-three minutes is out of the question. . . . It quite appals one to think of taking so long. The experience of most compressed-air works is that up to 27 pounds gauge pressure there is very little trouble, and using this as the safe limit, the times required to reduce the saturation in the blood to 27 pounds is not so excessive for pressures up to 50 pounds."

Based on the consideration that decompression from 27 pounds is fairly safe, Japp has constructed the following table, using Haldane's data as to circulation time of blood and rate of saturation :

JAPP'S DECOMPRESSION TABLE, BASED ON NINE MINUTES BEING SAFE FOR TWENTY-SEVEN POUNDS GAUGE PRESSURE.

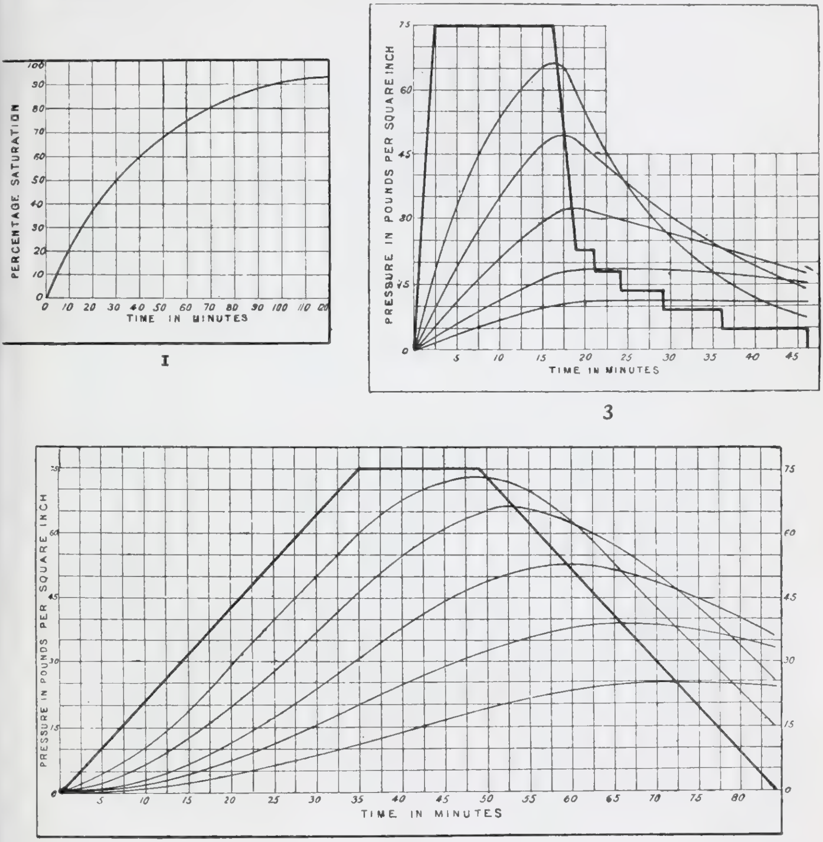
Gauge Pressure in Pounds.	Reduce Pressure in 3 Minutes to—	Total Time in Air-Lock after 8 Hours' Work.	Total Time in Air-Lock after 3 Hours' Work.	Total Time in Air-Lock after 2 Hours' Work.
	Lbs.			
27	6	9	—	—
30	7½	24	—	—
32	8½	33	25	—
35	10	—	35	—
40	12½	—	48	—
42	13½	—	51	37
45	15	—	—	42
50	17½	—	—	48

If hard exercise were taken, the circulation could be increased five or six times, and the decompression be safely reduced much farther. By also breathing oxygen a few minutes before and during decompression the time could be shortened very greatly. Bornstein calculates that the same volume of nitrogen expelled by uniform decompression in one minute would be expelled by stage decompression in 0·5 to 0·6 minute ; by breathing oxygen in 0·35 minute ; forced breathing in 0·5 to 0·9 minute ; light bodily work in 0·2 to 0·35 minute ; heavy bodily work in 0·1 to 0·2 minute.

Japp writes : " Some time after reading Dr. Haldane's paper and studying his theory, it became necessary to raise the pressure in the East River Tunnels to 40 pounds gauge. It was possible to make the workmen pass through three sets of air-locks on leaving the tunnel. The inner chamber was kept at 40 pounds, the intermediate chamber at 29 pounds, and the outer chamber at 12½ pounds.

" The men were ordered to take five minutes in the first lock, eight minutes in the second lock, and fifteen minutes in the third. There was a distance of approximately 1,000 feet between each pair of locks. Walking this distance and gathering in the stragglers generally required ten minutes to each chamber, so that, in all, forty-eight minutes were taken to decompress from 40 pounds to atmosphere. No severe or fatal cases resulted, and little time was lost by the men through caisson disease, the cases being only slight. Under this pressure 330 men were employed for thirty-six days, working three hours on, three hours off, and three hours on. It is true that no 'green' men were used on this work, as there were plenty of experienced air-men available at that time.

If a single lock had been used at 12½ pounds and very active exercise carried out in that, fifteen minutes probably would have sufficed.



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3

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Fig. 62.—1, Curve of Saturation of Body (Resting). 2, Uniform Decompression showing Super-Saturation of "Slow" Parts. 3, Stage Decompression lessening Saturation of "Slow" Parts (Theory of Haldane).

" In caissons or tunnels with but one lock, it is a difficult problem to allow workmen as long a time as the table indicates, as no one can enter the air-lock during decompression. One method of overcoming this difficulty would be to provide a lock with two small end chambers and a larger centre chamber, four doors in all being necessary. Anyone making a short visit to the caisson could pass through without disturbing the pressure in the middle decompressing chamber.

"The men on the East River Tunnels rebelled against fifteen minutes for decompression, but, after putting the responsibility up to the foremen, in time they found that it was a safeguard, and voluntarily lengthened the time to twenty minutes, and gladly submitted to forty-eight minutes for 40 pounds."

The results obtained by Japp's decompression method prove that the decompression periods given in the table of the Admiralty Committee are about twice as long as necessary. These periods undoubtedly can be considerably shortened if efficient exercise is taken in the air-locks, or by the diver during his ascent.

The practical conclusion of the above review is that while decompression times at caisson works are often too short, those tabled by the Admiralty Committee are unnecessarily long. Particularly is this so if the men be persuaded to exercise their bodies during decompression. While the evidence of the superiority of the stage over uniform method is not so marked as the Admiralty Committee maintained, there can be no doubt that the stage method can be made fairly safe, and is the best one to use for caissons.

A stage at +8 pounds, lasting fifteen minutes, seems to be enough after a shift at +30 pounds, and a stage of thirty minutes at +15 pounds after a shift at +40 to 45 pounds, provided a medical lock for recompression is at hand. Five minutes in the first, and ten minutes in the second case, should be given for completing the decompression. Von Schrötter recommends for +1 to 1½ atmospheres a shift of six to eight hours' decompression in ten minutes, quicker at first; for +2 atmospheres a shift of six to eight hours' decompression, to +0·8 atmosphere in three minutes, and then to +0 at rate of four minutes per 0·1 atmosphere; for +3 atmospheres a three to four hours' shift, decompression to +1·5 atmospheres in three minutes, and then to +0 at rate of four minutes per 0·1 atmosphere. If the men can be arranged to climb from top to bottom of the shaft during the stage it will greatly increase their safety. At the Greenwich Tunnel (on the writer's suggestion) the men were made to climb the ladder immediately after decompression. This distinctly lessened the number of cases of "bends." If really active exercise were taken the above periods probably could be safely halved.

CHAPTER XV

TREATMENT OF CAISSON SICKNESS—RECOMPRESSION

FRICTION, massage, and hot baths may be tried as a palliative for "bends," and a small injection of morphine given to relieve severe pain. Oxygen may be given the subject to breathe in severe cases, not only with a view to accelerate the diffusion of nitrogen out of the lungs, but to supply enough oxygen to keep life going when the circulation is dangerously obstructed by nitrogen bubbles.

All such measures are as nothing compared to the efficacy of recompression, by means of which men have truly been raised from the dead. Pol and Watelle, as far back as 1854, record the relief obtained by those who went back into compressed air. The men found out the cure themselves, and voluntarily went back when seized with "bends."

Bert demonstrated the value of recompression by his experiments on animals, and strongly recommended it. A. Smith suggested the use of a recompression chamber at the Brooklyn Bridge Works, and E. W. Moir instituted a "medical lock" at the Hudson Tunnel, and, proving its efficacy, made it an essential equipment of all caisson works.

The writer, in his experiments with the frog's web, saw the bubbles appear in the capillaries on decompression, and watched them shrink and disappear on recompression.

J. F. Twort and the writer have observed microscopically bubbles set free in water after decompression from +90 pounds, measured their diameter, and watched them shrink on recompression.

J. J. R. Macleod and the writer, among other experiments, record the following:

A large hutch rabbit was kept under a pressure of +7 atmospheres of air for two hours, and was then quickly decompressed.

In a minute or so the rabbit developed typical decompression symptoms (*i.e.*, fell on side, and limbs showed tetanic convulsions). The pressure was now quickly reapplied up to about +5 atmospheres by emptying a large cylinder of compressed air into the chamber. The symptoms, however, remained unabated, and the rabbit soon died. It was evident, therefore, that for the reapplication of pressure to be of any avail, the pressure must be very quickly re-established, and no time be given for the air bubbles to damage permanently the nervous tissues, or to produce stasis of the circulation for too long a period.

We therefore repeated the experiment, with the modification that the pressure was more quickly reapplied.

A cat and a hutch rabbit were subjected to an air pressure of +7 atmospheres for four hours. Decompression was effected to zero in about five seconds, and as quickly as the taps could be opened (about five seconds) a large cylinder of compressed air was delivered into the chamber, thus raising the pressure to 95 pounds in about two minutes.

At the moment of decompression the cat sprang to the window, excited and with widely dilated pupils. In a few seconds it became entirely paralyzed in the limbs, so that it fell helpless on to its side, its head meanwhile showed continuous side to side pendulum-like movements. There was no nystagmus. On recompression these symptoms gradually disappeared, the head movement being the first to go, then the pupils contracted to their normal size. Some two or three minutes after recompression to 95 pounds the cat tried to move about, but fell. The pressure was maintained for forty-five minutes and then slowly lowered. The cat recovered, and on removal seemed *perfectly normal*, and on being placed in his basket, leapt over its side and escaped into the room. Next morning it was quite normal in every respect.

The rabbit was recompressed before it showed any symptoms of decompression, and was quite normal on removal from the chamber.

The medical air-lock used at the East River Tunnel Works consisted of an air-tight steel cylinder about 6 feet in diameter and 12 feet in length, closed at one end. "At the other end is an entrance by means of a door which opens inward. The cylinder is divided into two compartments by means of a transverse partition, which has a door opening toward the inner compartment. Compressed-air pipes and outlet valves supply both chambers, so that the pressure may be raised or lowered from either chamber. This arrangement enables the physician or attendant to enter or leave the chamber in which the patient is being treated without disturbing the pressure. Valves are also placed outside the locks, so that the pressure may be regulated from without. The inner chamber is fitted with two bunks, one on either side, upon which patients may lie, and with electric lights, telephone, clock, pressure-gauge, thermometer, and electric heater. A means of ventilating the inner chamber is also supplied. Heavy glass windows are placed on a line in both doors, so that one may watch the patient, pressure-gauge, and thermometer from outside."

Keays says : " One who has seen the results of recompression cannot doubt its practical benefit. We can explain the failure of recompression to cure in certain cases by assuming that the gas emboli have done permanent injury to the tissues before treatment has been instituted. In general, the sooner recompression is used after the onset of symptoms, the more immediate and permanent the relief will be." The method of employing recompression which Keays found most efficient was to put the patient at once into the medical lock, and raise the pressure quickly to a point equal to that under which he had been working. " The pains were often relieved by a lower pressure, but the results were more likely to be permanent when full tunnel pressure was used. As soon as the pressure equalled the tunnel pressure, decompression was instituted, the full time for decompression being at least twice as many minutes as there were pounds of pressure. The best results were obtained when the pressure was reduced rather quickly to 10 or 15 pounds, from which point decompression was carried out very slowly. The patient, if able to move about, was told to do so during decompression, as it was found that exercise, and movement of the affected part especially, helped in bringing about a permanent relief. Not infrequently the symptoms return after decompression from the medical lock. In such cases a second recompression may be used. In some cases patients were recompressed three or four times before permanent relief was obtained."

Recompression relieved 90 per cent. of the 3,067 cases of pain so treated, and failed to give any relief in only 0·5 per cent. of the cases. Concerning these Keays says : " I found among the records of cases of pain eighteen in which recompression failed to afford permanent relief where full-tunnel pressure was not used. As another cause for the failure of recompression, I found the statement in several instances that the patient did not move about as directed during treatment, but went to sleep on one of the bunks."

"When treatment has been delayed more than six hours after the onset of symptoms medical means are on the whole more efficient than recompression."

The following cases of pain and prostration are cited by Keays. "The cases in general were treated by recompression and stimulation. The most severe cases were given massage of the trunk and extremities while under pressure. Most of them required more than one recompression, as the pains and weakness often returned after one treatment in the medical lock. Of the forty-seven cases of this class the results of treatment were as follows :

Three cases refused the medical lock, and were treated by rest and stimulation ; all recovered. One was in a hospital for one week. The others recovered at home after a few days.

Ten cases were relieved by one recompression, and were able to go home after a few hours' rest.

Two cases were relieved by one recompression, but still felt weak, and were sent to hospitals, from which they were discharged in a few days.

Twelve cases were relieved by two recompressions, and were able to go home after a few hours' rest.

One case was relieved of pain by two recompressions, but was sent to a hospital on account of weakness, and remained one week.

Seven cases were relieved by three recompressions, and were able to go home after a few hours' rest.

Five cases were relieved of pain by three recompressions, but because of weakness they were sent to hospitals, where they remained for periods of from one to seven days.

One case was relieved by four recompressions.

Six cases had only temporary improvement from recompression, and proved fatal.

In regard to cases showing symptoms referable to the central nervous system, Keays records four cases of hemiplegia, all cleared up permanently under one recompression.

The results of treatment of thirty-six cases of sensory disturbance of the spinal cord were as follows :

Two cases refused medical lock, and were improved by medical treatment.

Thirty-one cases were relieved permanently by one recompression.

Two cases were relieved by two recompressions. (One of these had difficulty in urinating, and had to be catheterized ; went home and did not report again.)

One case relieved by three recompressions.

The results of treatment of thirty-four cases of motor disturbances were as follows :

Of eighteen cases which had partial paralysis of the legs, twelve cleared up entirely under one recompression, six showed little or no improvement.

Of sixteen cases of complete paralysis of the legs, seven cleared up entirely under recompression, in nine there was little or no improvement.

The final results of these thirty-four cases were as follows :

Five were fatal. One case showed no improvement after two weeks, and died a few weeks later, but exact cause of death was not learned. Three cases had permanent spastic paraplegia. Two cases, final results not learned. Twenty-three cases recovered.

The results of treatment of ten cases of motor and sensory disturbances were as follows :

Of five cases with partial paralysis and numbness of the legs, four cleared up entirely under recompression, one case partly relieved by recompression (final result not known).

Five cases with complete paralysis and loss of sensation of legs all cleared up under recompression.

Of cases showing vertigo, either with or without vomiting, pain, prostration, and dyspnœa, the results of treatment in 197 cases were as follows :

Ninety-five cases, complete relief by one recompression.

Thirteen cases, complete relief by two or more recompressions.

Eighty-two cases, partial relief from recompressions.

Seven cases, partial relief from medical treatment.

Of the cases showing dyspnœa and sense of constriction of the chest, the results of treatment in sixty cases were as follows :

All were relieved by one recompression, except two, which required two recompressions.

The results of treatment in seventeen cases showing partial or complete unconsciousness or collapse were as follows :

Artificial respiration, massage, and stimulation were used in these cases in addition to recompression.

Three cases of semi-consciousness cured by one recompression.

One case of semi-consciousness improved by two recompressions.

One case of complete unconsciousness cured by one recompression.

Three cases of complete unconsciousness much improved by one or two recompressions, all right after a few days.

Nine cases of partial or complete unconsciousness, little or no improvement by recompression, resulted fatally.

This case is reported in full, as it illustrates well cases of this class in which the onset is fairly sudden, and also the beneficial results of recompression. A. M., Hungarian, aged twenty-six, had been working steadily in compressed air for several months. On October 8, 1907, after working from 7 to 10 a.m. and from 1 to 4 p.m. under +34 pounds pressure, went home, a few blocks away from the works. At about 4.45 p.m. he began to have general pain and weakness. A brother came at once to the doctor's office, where I happened to be at the time, and told me that his brother was ill. I went with him, and found the patient lying on the bed crying out with pain, which he said he felt all over. He was pale and cyanosed, and perspired freely. His pulse was much increased in rate and was weak. Recognizing that it was a severe attack, I advised that he be recompressed as soon as possible. A Bellevue ambulance was called. Before the ambulance arrived, the patient became unconscious, the respirations were stertorous, and the radial pulse became almost imperceptible. When the patient was moved from the bed to a stretcher, he stopped breathing for what seemed to be a minute or more. The radial pulse disappeared, and it seemed that he was dying. Strychnine sulphate, $\frac{1}{30}$ grain, was given hypodermically. Respirations were again resumed, and a hurried transfer was made to the medical lock, where recompression was begun at 5.15 p.m. As the pressure was raised general massage was given. For some time there was no improvement in his condition, but at about six o'clock slight improvement was apparent, when his colour was better and the pulse could be felt. At 6.30 he regained consciousness, and could answer questions. Colour, fair; pulse, 90, irregular; respiration, 28. He could sit up, but felt very weak. During the time that the pressure was being very slowly reduced, he continued to improve. Mottling was marked at one time, but became fainter. Recompression was completed at 11 p.m. A note of his condition then was as follows: "Wholly conscious, can sit up with difficulty, colour good, no sweating. Pulse still weak, 120 per minute; heart and lungs normal, abdomen very tender, but not rigid or distended; mottling faint. Temperature, 98½° F.; no paralysis."

He was transferred to the New York Hospital, where his condition continued to improve. He was discharged from the hospital on October 12, 1907, and reported at the works cured.*

When no treatment is adopted, the bubbles ultimately disappear of themselves. The bubbles are compressed during the muscular movements of the body, and the pressure of the nitrogen raised above that dissolved in the blood. Thus nitrogen will slowly diffuse out of the bubbles, and they will ultimately disappear. The nitrogen bubbles in the blood may leak out bodily through the lungs. It takes very little pressure to make air pass from the lung alveoli into the blood. The lungs are, in fact, astoundingly leaky to air; and unless air leaks out bodily from the blood into the lungs, it is very difficult to understand how small the effects sometimes are of slowly injecting enormous quantities of air into an animal's veins.

Recompression chambers are not available in connection with ordinary diving work, but, as the Admiralty Committee point out, "there remains the possibility of sending a diver down again should any serious symptoms threaten, should he be accidentally 'blown up' to surface, or should he from any other cause have come up, or been hauled up, more quickly than is safe. There is an interval of some minutes at least before symptoms develop in consequence of rapid decompression; and if, for instance, a man has been blown up, there is plenty of time to haul him in, ease his valve, and send him down again. Even if very serious symptoms have already developed, and he is helpless, it is far safer to open his valve, give him plenty of air, and drop him down slowly and steadily on the life-line till he recovers or the bottom is reached. He will probably have recovered by the time he is down a few fathoms, and another diver can be sent after

---

* Mr. E. W. Moir reports a case, and the writer has seen a case of severe "bends" cured by recompression applied several days after the onset.

him shortly. If he has no symptoms, he can go down himself in the ordinary way until a safe depth is reached.

"In any doubtful case, where symptoms seem possible, though not probable, the diver, on coming to surface, might remain in the water or on the diving ladder for ten minutes before coming on board and having his helmet unscrewed. He could thus very easily again descend if he began to feel any symptoms. On coming on board he ought not to undress for another twenty minutes."

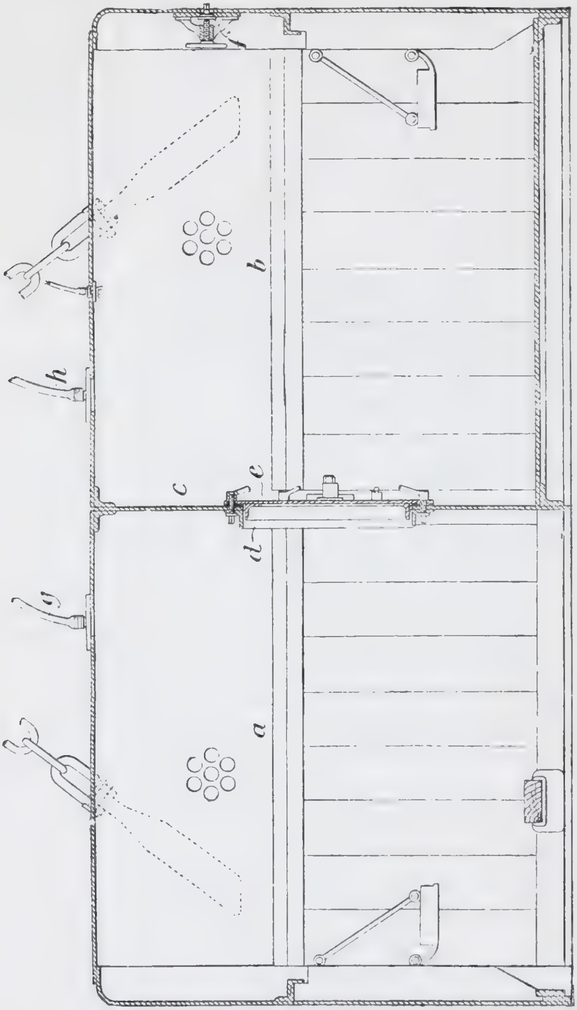

Fig. 63.—Decompression Chamber for Divers (Siebe, Gorman and Co.).

For deep-diving work the writer has contrived a decompression chamber. This consists of a double-chambered diving-bell, one chamber (*A*) open at the bottom to the sea, the other (*B*) closed save for a manhole communicating with *A*. The bell is lowered to the bottom, and the divers, after completing their work, enter *A*, and from thence pass into *B*, and close the manhole. The bell is then raised on deck, and *B* is slowly decompressed.

The pressure in the chamber could be reduced very greatly within a few minutes, so that even if it were hauled rapidly to the surface it would not require to withstand an excess of internal pressure of more than 1 or 2 atmospheres.

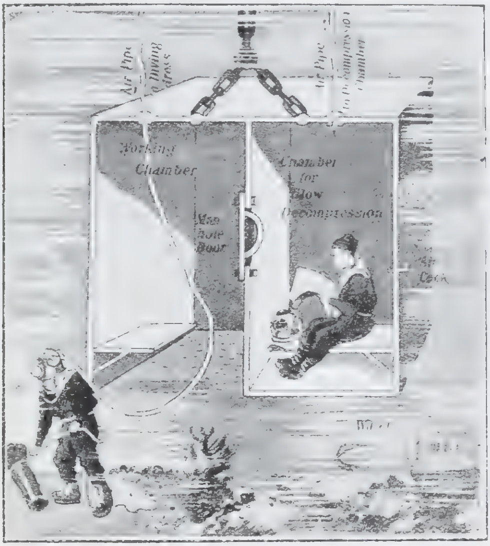

Fig. 64.—Sketch of Decompression Chamber in Use.

The Admiralty Committee reported that: "Several advantages would be gained by the use of a submerged decompression chamber in this way. In the first place, the diver would be spared the long and tedious ascent through the water. During the ascent he is exposed to the risk of his hands becoming numbed from cold, so that he cannot hold on to the shotted rope. If, as is often the case, the tide is formidable, the risk of being carried away from the shotted rope is, of course, considerable, and a diver thus carried away will probably come to the surface at once, and so be in danger of the consequences of sudden decompression. A second advantage of the submerged decompression chamber would be that in the event of any symptoms occurring the diver could be recompressed at once. A third advantage would be that if his air-pipe was attached to the chamber he would be saved the very formidable drag caused by the tide acting on an air-pipe coming from the surface, and he could thus work as easily at great depths as he could near the surface, with a tide running.

"Another plan available for prolonged work in deep water would be to use a diving vessel provided with a caisson about 3 feet in diameter, passing by a well through the bottom to a point some 30 or 40 feet below the surface of the water. This caisson would be open below, and would end above, inside the diving vessel, in an air-tight chamber, provided with an air-lock for passing in or out, or two air-locks, one of which could be used for recompression if necessary. The shotted rope would be attached to the open end of the caisson. The diver could go down to his work in the ordinary way from the ship's side, but on coming up could enter the caisson at its open end, and be brought up to the chamber at the upper end. He would thus be saved the long waits in the water during the later and longer stages of stage decompression, and he could be decompressed at leisure, in the air-lock, after a wait sufficiently long to make the process safe. With this arrangement, if the excess of pressure in the caisson was 1 atmosphere (33 feet of water), and if sufficient time were taken before coming out from the caisson, it would be possible for a diver to work at double the absolute pressure without increasing the risk from decompression. For instance, at 30 fathoms the absolute pressure is double that at 12¼ fathoms ; hence the diver could return as safely to the caisson from 30 fathoms as he could to the surface from 12½ fathoms. A vessel fitted out with a movable caisson (used as a diving bell) was recently supplied to the Admiralty for use at Gibraltar."

A recompression chamber ought to be on hand in all important deep-sea diving works. The men engaged in caisson works—run at dangerous pressures—should have barracks at the works, and remain there after the shift, so that they may be at once recompressed on first sign of illness. The onset of illness is often delayed even for an hour or more, for it depends on the accumulation of bubbles and stoppage of the circulation in some vital part.

In experiments on pigs we have several times lost the animals on their way home to the farm, after we had, as we thought, safely decompressed them. We have failed to cure pigs, dangerously affected, by recompression when the interval has been more than a very few minutes.

The ordinary air-locks provided in caissons are too small and uncomfortable to permit of the long pause required in a stage decompression, and offer no room for the carrying out of bodily exercises, which are essential if the period of decompression is to be diminished safely.

In the East River Tunnels, which were 23 feet in diameter, three air-locks were placed in each bulkhead, two for materials and one for men. This meant that the air-lock was a cylinder about 6 feet in diameter, and it would be impossible to keep gangs of workmen, numbering thirty or more, in such a lock for an hour or more. Air-locks of a similar size were used in the Rotherhithe and other tunnel works in London visited by the writer. Haldane has proposed that the first section of the tunnel might be used, in which a pressure equal to one-half the absolute tunnel pressure could be maintained. Entrance to this chamber could be gained by air-locks, one leading into the tunnel and the other into the open air.

Fig. 65.—Hall and Rees' Dress for escaping out of Submarines (Siebe, Gorman and Co.).

There is a box containing oxylithe under the dress, and a tube leads from this and opens into the top of the helmet. Another tube leads from the box to a mouthpiece. The subject breathes the air in the helmet through the oxylithe, which absorbs CO_2 and gives off O_2. The buoyancy of the air carries him to the surface when the submarine has been flooded and the conning-tower opened. By means of the tube and tap, A, B, D, he can blow out a swimming-belt, and so float on the surface and open the window.

In this "purgatory chamber" baths and lockers could be provided, and the men could occupy the time in changing their clothes, washing, and have hot coffee served to them to stimulate the circulation. They could also breathe oxygen for a few minutes just before the final decompression to the atmospheric pressure.

By proper attention to such matters engineers might carry out without excessive risk to life works at depths which they do not now attempt.

The men employed for such works would have to be carefully selected; there should be chosen young, spare, men, with good pulmonary ventilation and circulation, temperate in habit, moderate eaters, free from flatulence. They should live the life of athletes in training, and avoid fat food. Their suitability might be tested by one trained in physiological methods. One of the simplest and best methods of testing the condition and training of the men is to see how quickly the pulse frequency drops to the normal resting value after the performance of a piece of hard work. The men could be tested in this way, and some idea of their efficiency obtained. The writer found the pulse frequency dropped in the case of a well-known prize-fighter from 170 to 70 in one minute after a period of boxing. The frequency produced by exercise keeps up for some time when a man is out of training and overdone. Another guide to suitability is the respiratory exchange per kilogramme of body weight. This can be measured in the following way: The subject is placed recumbent and completely at rest. The observations are taken before breakfast—*i.e.*, twelve hours after a light supper. He breathes through a mouthpiece fitted with inspiratory and expiratory valves; the expiratory valve opens into a large rubber flat bag (squeezed empty of air). The inspiratory valve opens from the atmosphere. The man breathes for ten minutes into the bag. The expired air in the bag is then pressed through a meter, and its volume recorded, while a sample of it is collected, and the percentage of CO_2 and O_2 determined. From these data, and from the weight of the man, the use of O_2 and output of CO_2 per kilogramme of body weight per minute is calculated. Several such observations are required and the mean is taken.

While there is no such thing as immunity to caisson sickness, individual susceptibility varies considerably, as has been established by experiments on animals and the practical experience of caisson workers. This makes it important to graduate the work of new men ("green" hands). All new men should be given a thorough physical examination, and any evidence of organic disease should cause rejection of the applicant. Old, heavy, fat, and alcoholic subjects should be rejected. Let it be remembered that old, fat men have a lower rate of respiratory exchange and less blood in proportion to a mass of tissues; the blood may be one-thirtieth of the body weight in a fat man, and one-twentieth in an average man. Alcoholism may increase the fatness both of the liver and blood. At the East River Tunnels 20 per

FIG. 66.—THE SUBMARINE DRESS WEIGHTED AND USED AS A DIVING DRESS FOR SHALLOW WATER (SIEBE, GORMAN AND CO.).

The diver must not bend down in using this dress.

cent. were rejected. The new men should be tested in their first shift or two to a period of one to two hours, and men having symptoms of illness after this period should be rejected. If a considerable pressure is being used—over +30 pounds—it were best to test the new men first at a pressure not exceeding +30 pounds.

Many men suffer from repeated slight attacks of "bends," itching of the skin, and there is no need to reject them on account of such slight symptoms.

The health of the old hands should be watched, and re-examination made after any absence from the works. The men should be instructed in the need for slow decompression and of prompt treatment by recompression, the dangers of over-indulgence, over-fatigue, or loose living, and necessity of keeping in vigorous health, sound in heart and lung, and free from flatulence. They should be taught also how exercise during decompression is of the greatest value in adding to their safety and freedom from "bends."

The writer confidently looks forward to the carrying out in the future of some essential and important work at a pressure of even +60 pounds by a carefully picked and trained body of young men. Such can be made safe by a one-stage decompression of half the period laid down by the Admiralty Committee, if exercise be taken during the pause; and in less than half this period if oxygen is breathed during the stage decompression.

Von Schrötter has devised an apparatus to allow the breathing of a mixture of oxygen and hydrogen (or methan) during decompression from high pressures. The hydrogen is used to dilute the oxygen. As the pressure is lowered, the oxygen percentage is increased and the hydrogen diminished till, finally, oxygen alone is supplied in the last stage of decompression. This seems a possible method, but the explosive nature of the mixture is a great deterrent to its adoption.

While the last pages of this book are passing through the press, R. H. Davis (Siebe, Gorman and Co.) and the writer have modified the diving-dress in such a way that oxygen can be breathed during decompression from the +30 pound stage to +0 pound. The installation of oxygen-generating apparatus, and the use of such a dress at the Australian pearl fisheries, may help to open rich and untouched beds of shell.

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